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Evolution of Sensory Systems in Snakes: Infrared Detection, Chemoreception, and Ecological Adaptation

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Abstract This article briefly reviews the evolution of snake sensory systems, focusing on three main sensory methods: infrared perception (the ability to "see" heat), chemical perception (smell through the tongue and vomeronasal organ), and mechanical perception (like touch and vibration sensing). Snakes are particularly unique in infrared perception. For example, vipers, pythons, and anacondas have a "cheek pit" structure on their faces that can sense subtle changes in heat, allowing them to find prey in the dark. Snakes also constantly stick out their tongues to collect odors and analyze these chemical information through the vomeronasal organ to track prey, find mates, and distinguish between their own kind. Aquatic snakes, such as sea snakes, have also developed more sensitive skin sensors that can sense changes in water pressure and better adapt to underwater environments. The article also talks about how these sensory abilities work with the snake's brain, and also talks about related genetic changes and environmental pressures, such as nocturnal habits, underground life, and how different species divide labor. By comparing with lizards, crocodiles, and birds, the special features of the snake sensory system are further explained. Finally, the author points out that with the development of genetic technology, brain imaging and bionic engineering, the study of snake senses can not only help us understand how animals perceive the world, but may also bring new inspiration to artificial intelligence and robotics.
Keywords Infrared detection; Vomeronasal chemoreception; Ecological adaptation; Neural integration; Bionics application

1 Introduction

Snakes have developed special sensory abilities over a long period of evolution. They can sense infrared heat and can detect odors very sensitively. These two abilities are particularly important when they hunt, survive, and reproduce. These two sensory methods are also key clues to understanding how snakes adapt to various environments (Schraft et al., 2019; Peng et al., 2023). It is very meaningful to study the sensory system of snakes. Because these abilities not only show the unique evolutionary path of reptiles' senses, but also provide a good example for studying how animals perceive the world through multiple senses together. For example, many snakes have poor eyesight, but they rely on an organ called "cheek pit" or "lip pit" to sense subtle changes in temperature. In this way, they can "see" warm-blooded prey even in the dark (Clark, 2004; Zou et al., 2024).

In addition, snakes will constantly extend their tongues to collect odor molecules in the air, and then use the vomeronasal organ (also called the Eucobusson organ) to "smell" these odors to find food or recognize information in the environment (Gracheva and Ingolia, 2011). Because of these abilities, snakes have become a good subject for studying animal perception and behavioral adaptation. In recent years, with the progress of genetic research and neuroscience, these sensory systems of snakes have been used as a good model for studying animal evolution (Peng et al., 2023; Zou et al., 2024). There are many types of snakes and they are widely distributed. Some are active during the day, some are active at night, some live in caves, and some live in water. Snakes in different environments also have different vision, thermal sensation, and smell. This provides scientists with a good opportunity to compare different types of snakes, and to more clearly see the connection between perception and living environment.

One study found that different species of snakes have become genetically similar in two areas: sensing heat and smelling. But in other areas, their genes are still quite different. These results not only give us a better understanding of how snakes evolved, but also help us understand how animals like vampire bats have similar abilities. This article focuses on two sensory abilities of snakes: sensing heat and smelling. We will look at what new research scientists have done in the past five years to understand where these abilities come from, what their organs look like, how they work in the body and brain, and how these abilities are related to the snake's living environment. We will also compare snakes with other reptiles to see which have stronger sensory abilities. Finally, we will talk about how to study these issues in the future and what we might do with this research. Our goal is to understand how snakes' sensory systems have evolved step by step and how they help snakes adapt to various environments.

2 Evolutionary Origins: Evolution of the Sensory System in Snakes

2.1 Fossil evidence and ancestral reconstruction

Scientists have found clues to the evolution of the sensory system of snakes through fossil and genetic research. Studies have found that the inner ear structure of snakes is very similar to that of modern burrowing reptiles. This shows that the ancestors of snakes mostly lived underground (Yi and Norell, 2015). In addition, snakes have lost many genes related to light during evolution. The disappearance of these genes indicates that early snakes may have lived in very dim places, and this change occurred before they lost their limbs (Emerling, 2017). Later, scientists studied the visual pigments of snake ancestors and found that their eyes' light sensitivity had begun to degenerate. Some rhodopsins that were originally used for seeing things have disappeared. However, they have not completely lost these functions like some extreme burrowing snakes today (Simões et al., 2015).

2.2 Early divergence and sensory adaptation in snake lineages

Snakes were divided into many different species in the early stages of evolution. These snakes also underwent many changes in their sensory abilities. For example, studies have found that snakes have undergone significant changes in their genes and body structures in terms of infrared perception, vision, touch, etc. (Peng et al., 2023). For example, some snakes have acquired the ability to sense heat through an ion channel called TRPA1. They have a structure called "cheek pits" on their faces that can sense temperature differences, thereby forming a "thermal image" to find prey or avoid enemies (Gracheva et al., 2010; Peng et al., 2023). Some snakes have also changed their retinas. For example, the retinas of daytime colubrid snakes are "all-cone". Although they look like cone cells, they are actually rod cells. This change helps them adapt to daytime light and also makes up for the problem caused by the loss of medium-wavelength rhodopsin (Schott et al., 2015). In addition, sea snakes living in water have some special changes. Their tails can sense light, and there are more mechanical receptors on their skin. These changes help them move better underwater (Crowe-Riddell et al., 2019a; 2019b).

2.3 Evolutionary pressures: burrowing, arborealism, and predation

The reason why the sensory systems of snakes vary so much is that they live in different environments. Snakes living underground have poor vision and their eyes are not used because the light is too weak, so the relevant genes are gradually lost (Schott et al., 2015; Simões et al., 2015; Emerling, 2017). But snakes living in trees or water are the opposite. They need to perceive more external information, so they have developed stronger tactile and light perception abilities. For example, the tail of sea snakes can sense light, and the mechanical receptors on the head are also particularly obvious (Crowe-Riddell et al., 2019a; 2019b).

In addition, the need for predation has also driven these changes. In order to better hunt, snakes have evolved infrared sensing capabilities. With this ability, they can detect warm-blooded prey even at night or in dim light (Gracheva et al., 2010; Peng et al., 2023). As snakes have more and more ways to hunt, their sensory systems are becoming more and more diverse. This also allows different species of snakes to differentiate faster in evolution and adapt to different ecological environments (Title et al., 2024).

3 Infrared Detection in Snakes

3.1 Mechanism: Pit organs, neural circuits, and thermal imaging

Snakes can "see" infrared rays because they have a special structure on their faces called the "pit organ". This organ can sense the heat emitted by the body of prey or enemies. It helps snakes find the location of their targets (Gracheva et al., 2010; Darbaniyan et al., 2020). When heat (that is, infrared rays) shines on the pit membrane, the temperature of the membrane rises. There are many nerves in the membrane, and these nerves can sense temperature changes. Scientists have discovered that there is a channel called TRPA1 on these nerves. This channel is particularly sensitive to heat and is the most sensitive of all vertebrates discovered so far (Gracheva et al., 2010). In addition, the cells of the pit membrane are also very special. They are a bit like thermoelectric materials and can convert heat into electrical signals (Darbaniyan et al., 2020). These electrical signals will be transmitted to the snake's brain and sent to a place called the "optic tectum". This place can also receive visual information from the eyes. The brain will combine these two signals so that the snake can determine where the prey is (Hartline et al., 1978). Although these "thermal images" are not as clear as those taken by a camera because these small pits cannot be focused, the snake's brain is very smart. It can process these vague signals and help the snake find the target more accurately (Sichert et al., 2006; Clark et al., 2022).

3.2 Phylogenetic distribution (e.g., boids, pythons, pit vipers)

Not all snakes have infrared perception. Only three types of snakes have this ability: boids, pythons and pit vipers (Ebert and Westhoff, 2006; Gracheva et al., 2010). All three types of snakes have pits, but their location and structure are slightly different. Snakes in the Viperidae family, such as rattlesnakes, have pits between the eyes and nostrils. The structure is very complex and the perception is particularly sensitive. In the case of snakes of the Anaconda and Python families, such as ball pythons, the cheek pits are located in the scales of the upper lip (Ebert and Westhoff, 2006; Gracheva et al., 2010). Studies have found that ball pythons can "see" heat sources as large as mice from 30 cm away, while western rattlesnakes can sense heat from a distance of up to 100 cm. This shows that different snakes have different infrared perception abilities (Ebert and Westhoff, 2006; 2007).

3.3 Comparison with infrared perception in other animals (e.g., vampire bats)

Some other animals, such as vampire bats, can also sense heat. However, their mechanisms are different from those of snakes. Snakes "sense temperature" through TRPA1 channels and thermal radiation, while bats use special structures on their faces to sense temperature, but they use different molecular mechanisms than snakes (Gracheva et al., 2010; Darbaniyan et al., 2020). Another special thing about snakes is that they can use thermal perception and visual information together. So even in the dark, they can accurately find their prey. This ability is rare in other animals (Hartline et al., 1978). Although the resolution of snakes' cheek pits is not as good as that of thermal imaging cameras, it is enough. It helps snakes find prey smoothly and allows them to survive in various environments (Sichert et al., 2006; Clark et al., 2022).

4 Chemoreception and Jacobson’s Organ

4.1 Anatomy and physiology of vomeronasal system

The vomeronasal organ of snakes is located above the mouth and is a structure that specializes in “smelling”. It belongs to the vomeronasal system, which looks a bit like the main olfactory system, but does different things. The vomeronasal organ transmits the chemical signals it receives to the “auxiliary olfactory bulb” of the brain through a different neural pathway, which is important in hunting and social interaction (Bellairs, 1942; Halpern, 1987). Scientists have discovered under a microscope that the tongue of snakes and the structures in their mouths work closely together. When snakes stick out their tongues, they bring back odor molecules from the outside world and send them to the opening of the vomeronasal organ. This allows snakes to “smell” the surrounding chemical signals more efficiently (Bellairs, 1942; Meredith and Burghardt, 1978; Gillingham and Clark, 1981).

4.2 Tongue-flicking behavior and trail following

Snakes often stick out their tongues to "smell" the air. When the tongue is extended, it brings back some odor molecules. When the tongue is retracted, these odors are sent to a place above the mouth. That place is connected to a structure called the "vomeronasal organ". Studies have found that if this structure is damaged, snakes can hardly smell the food (Gillingham and Clark, 1981). This shows that this part is particularly important to snakes and is mainly used to process odors. Some electrophysiological experiments have also proved this point. After the snake sends the odor to the vomeronasal organ, the nerves in its brain will respond immediately. These nerves are specifically used to process odor information (Meredith and Burghardt, 1978). Snakes stick out their tongues not only to find food. They also use this action to track the source of the odor. Sometimes, they also use this method to "see" the surrounding environment (Burghardt, 1993; Schwenk, 1995).

4.3 Role in prey detection, mating, and territory marking

Snakes use the vomeronasal organ to do many things, such as finding prey, finding partners, and even marking their own territory. Studies have found that young snakes can use their vomeronasal organs to respond to specific prey even before they have eaten. For example, they will stick out their tongues more often and even open their mouths to prepare for an attack. This shows that this reaction is innate and can also reflect what they may like to eat in the future (Burghardt, 1993). Snakes can also use chemical signals to find the opposite sex to complete the courtship process, and the vomeronasal organ also plays an important role at this time (Bellairs, 1942). In addition, snakes can distinguish the feces of individuals of the same species by smell, and use this method to recognize who the other party is, and can also mark their own range of activities (Burghardt, 1993; Schwenk, 1995). These findings tell us that the chemical perception system of snakes plays a very critical role in their adaptation to the environment and the development of various behaviors.

5 Neural Integration and Sensory Information Processing

5.1 Central nervous system adaptation of multimodal integration

Snakes have very smart brains. They can combine information from different places, such as what they see with their eyes and what they smell with their noses. In this way, snakes can judge whether there is prey or an enemy in front of them. Scientists have found that there are several particularly important areas in the snake brain, such as the amygdala, pulvinar, and epithalamus. When these areas see something curvy like a snake, they are particularly sensitive (Almeida et al., 2015). This shows that snakes can quickly recognize things that are dangerous to them or prey that can be eaten. In addition to their eyes, snakes also use their noses and vomeronasal organs to smell. This odor information is first sent to the olfactory bulb and then to other parts of the brain (Martínez-Marcos et al., 2002). These places are like "information transfer stations" that can piece together various sensations to let snakes know what is happening around them.

5.2 Thermal perception and olfactory-related brain areas

Snakes can sense heat and smell odors, and they have dedicated areas in their brains to process this information. The amygdala not only quickly distinguishes visual dangers, but also receives odor signals from the nose and vomeronasal organ. These signals are sent to the hypothalamus to help snakes take actions, such as sticking out their tongues to find prey (Martínez-Marcos et al., 2002; Almeida et al., 2015). There are also some brain areas such as the "globose nucleus" that also process information from smell and the vomeronasal organ. They work with the olfactory bulb and other parts of the telencephalon to integrate odor information and ultimately send signals to the neural areas that control tongue movements. These processes directly affect the hunting behavior of snakes (Martínez-Marcos et al., 2002).

In addition, because different snakes live in different environments, the parts of their brains responsible for smell and vision also look different. For example, snakes that are active during the day and snakes that are active at night have differences in these brain areas (Segall et al., 2021).

5.3 Cognitive significance: learning and decision-making in predation

Snakes not only act on instinct, they can also use the integrated information to "think". Studies have found that snakes use vision, smell, and thermal perception to quickly identify whether they are prey or enemies (Martínez-Marcos et al., 2002; Almeida et al., 2015; Bertels et al., 2020) (Figure 1). These abilities can improve their hunting success rate and allow them to escape danger faster. Interestingly, human infants also have special brain reactions when they see snake patterns.

This shows that our rapid recognition of snakes may be an instinct preserved in evolution (Bertels et al., 2020). This also shows that the perception system of snakes is not just part of animal behavior, it is actually related to the "cognitive contest" between predators and prey. In addition, whether snakes will stick their tongues out after smelling the smell is also related to their olfactory system. This connection shows that snakes can learn to make decisions in complex environments instead of just acting on instinct (Martínez-Marcos et al., 2002).

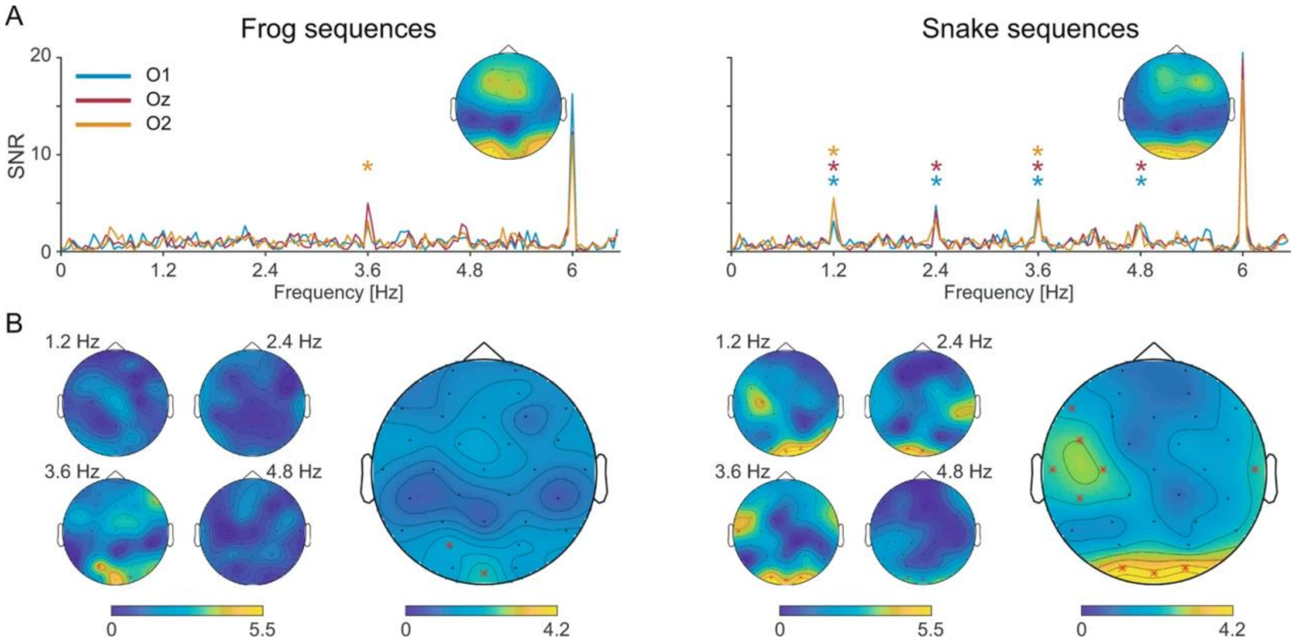

Figure 1 Frequency-domain representation of frog and snake-selective responses during fast periodic visual stimulation (left and right panels, respectively). (A) SNR spectra of each occipital electrode (O1, Oz, O2) and topographical maps of SNR at the base frequency (6 Hz). Asterisks indicate significant oddball responses. (B) Topographical maps of SNR at each harmonic of the oddball frequency (1.2, 2.4, 3.6, and 4.8 Hz; left part), and of SNR averaged on these first four harmonics (right part). Asterisks indicate significant responses at specific channels (Adopted from Bertels et al., 2020)

6 Impact of Ecological Drivers on the Evolution of Snake Sensory Systems

6.1 Habitat complexity and ecological niche

Snake sensory systems are closely related to where they live. Different environments, such as water, land, and underground, place different demands on snake sensory abilities. For example, sea snakes' eyes have also changed to adapt to underwater life. Studies have found that their visual proteins have undergone a "blue shift", which makes them more suitable for seeing underwater light dominated by blue light (Seiko et al., 2020). The internal structure of snakes' heads, that is, the morphology of the endocranium, will also change due to different living environments. These changes will affect how snakes maintain balance, how they perceive direction, and how they process sensory information (Segall et al., 2021). These studies show that environmental diversity and different ecological niches are important reasons for driving the diversified evolution of snake sensory systems (Seiko et al., 2020; Segall et al., 2021; Peng et al., 2023).

6.2 Nocturnality and underground life strengthen non-visual senses

Many snakes are active at night or live underground. The light in these places is poor, so their non-visual perception becomes particularly strong. For example, infrared perception has evolved in different types of snakes. This shows that they have independently "invented" this skill. This perception is related to some genes (such as TRPA1 and TRPM2), and their nervous systems have become better at processing heat signals (Peng et al., 2023; Zou et al., 2024). In addition, snakes living in the dark have more sensitive senses of smell and chemical perception, which can make up for the parts that the eyes cannot use (Segall et al., 2021; Peng et al., 2023). These changes show that the lighting conditions of the environment will deeply affect how the sensory system of snakes evolves.

6.3 Niche differentiation of co-local snakes

Some snakes live in the same place, but they avoid competition through "division of labor". This niche differentiation of "you eat this, I eat that" also promotes the diversification of their sensory systems. For example, in order to adapt to underwater life, the skin of the tail of some sea snakes has become photosensitive. This helps them better sense changes in their surroundings, such as avoiding predators (Crowe-Riddell et al., 2019a). For another example, some venomous cobras have evolved venom that is more potent, specifically stimulating the nerves of mammals and causing them pain. This change is also related to defense, as venom molecules become stronger under pressure (Kazandjian et al., 2020). These examples show that niche differentiation not only affects how snakes act and look, but also deeply affects how their sensory abilities evolve step by step (Crowe-Riddell et al., 2019a; Kazandjian et al., 2020).

7 Case Study: Pit Viper Infrared Sensing and Hunting Efficiency

7.1 A Detailed study of the crotalinae

Snakes of the subfamily Agkistrodoninae, also called "pit snakes" or "aggressors," have a special structure on their faces called a "pit organ." This small organ can sense very small changes in temperature. Even in the dark, they can "see" where their prey is (Safer and Grace, 2004; Darbaniyan et al., 2020; Tu et al., 2020). Genetic studies done by scientists have found that these snakes rely on a gene called TRPA1 to sense infrared light. But they rely on more than just this gene. Other genes related to ion channels, cell membrane voltage, and body temperature regulation are also at work. These genes became more active as pit vipers evolved. This made them more sensitive to heat (Tu et al., 2020).

7.2 Experimental study on thermal detection and attack accuracy

Many experiments have found that pit vipers use both their eyes and thermal sensors when hunting. If they are only allowed to use one of them, such as covering their eyes or thermal sensors, they can still catch prey, but their efficiency will decrease. However, they can still successfully catch prey in about 75% of the tests. When the eyes and thermal sensors on the same side are covered, they will attack to the other side; if the opposite side, that is, the cross side, is covered, their performance is the worst, and their success rate even drops below 50%. This shows that the information from the eyes and thermal sensors must be used together in the brain to allow it to attack accurately (Chen et al., 2012). In addition, the effectiveness of the infrared system will also be affected by the background temperature. If the prey is hotter than the background, it can be clearly located; but if the background is hotter, then the system will not work well. This suggests that pit vipers rely on “thermal contrast” to judge targets, just as our eyes rely on “light-dark contrast” to identify objects (Dyke and Grace, 2010; Chen et al., 2017).

7.3 The relationship between sensory specialization and ecological success

The heat sensors of pit vipers allow them to hunt successfully at night or in low light conditions. Even if their eyes are not working well, they can still pounce on warm-blooded animals accurately (Safer and Grace, 2004; Chen, 2017). Compared with other snakes without such sensors, pit vipers react more strongly to "hot targets", such as sticking out their tongues, turning their heads, and actively attacking. As for cold targets, they are unlikely to attack them even if they smell like prey (Safer and Grace, 2004). This special perception ability not only makes them better hunters, but also makes it easier for them to adapt to different environments. As a result, pit vipers have become a very distinctive and highly adaptable predator in the ecosystem (Tu et al., 2020; Darbaniyan et al., 2020).

8 Comparative Insights from Other Reptiles

8.1 Sensory system comparison with lizards, crocodiles and birds

Snakes have a very unique sensory system among reptiles. Compared with scaly species such as lizards, snakes have their own unique developments in seeing, smelling, sensing temperature and pressure. For example, vipers, pythons and anacondas have evolved a heat-sensing structure called "cheek pits" that can sense infrared heat and even see the location of prey like a "thermal imager". This ability is almost non-existent in other reptiles, including most lizards, crocodiles and birds (Gracheva et al., 2010; Peng et al., 2023). Snakes also have a very unique sense of hearing. They cannot hear sounds in the air, but they can very sensitively sense vibrations on the ground. This is completely different from the air-transmitted hearing of lizards or birds (Hartline, 1971). There are also receptors on the head - aquatic snakes like sea snakes have small structures on their head that can sense pressure, which helps them sense the environment in the water (Crowe-Riddell et al., 2016; 2019). Birds and crocodiles rely mainly on vision and hearing, and do not have these thermal or mechanical sensors at all.

8.2 Evolutionary convergence and divergence

Snakes have sensory systems that are similar to those of other reptiles, but they also have many differences. For example, snakes and some lizards have a good sense of smell. They can quickly find food with their noses and vomeronasal organs, and can also smell changes in the surrounding environment (Segall et al., 2021; Peng et al., 2023). But snakes "invented" the ability to sense infrared rays. Other reptiles do not have this ability (Gracheva et al., 2010; Peng et al., 2023). There are also differences in touch. Snakes that live in water, such as water snakes and sea snakes, can sense water flow and slight touch with scales on their heads. This is different from the receptors of land snakes, which shows that they have gradually adapted to the new environment in the water (Crowe-Riddell et al., 2016; 2019). Snakes also have different brains depending on the species. Those snakes that live by vision or smell have more developed related areas in their brains. These differences are actually related to how and where they live (Segall et al., 2021).

8.3 Uniqueness of the sensory system of snakes (paragraph style)

Snakes have a very unique sensory system among animals, especially in terms of heat, touch, hearing, and adaptation to the environment. First, some snakes can sense infrared rays, that is, heat. This is mainly achieved by sensing temperature changes through a channel called TRPA1. They can "see" heat sources, such as the location of warm-blooded animals. This is currently the most sensitive thermal sensing ability among vertebrates (Gracheva et al., 2010; Peng et al., 2023). Secondly, their head sense of touch is also very strong. Especially for sea snakes, which live in water, the scales on their heads are covered with small sensors. These things can sense water flow and slight touches, which is very suitable for underwater life (Crowe-Riddell et al., 2016; 2019). Snakes also have a unique sense of hearing. They are not very sensitive to sounds in the air, but can clearly feel vibrations on the ground or on their bodies. Studies have also found that snakes' lungs can also help them "hear", which is very rare in other vertebrates (Hartline, 1971). Most importantly, snakes' sensory abilities are closely related to their lifestyles. Different snakes have evolved different sensory abilities because they live in different places, eat different foods, and have different activity habits. These changes allow snakes to survive well in a variety of environments, adapt quickly, and survive successfully (Segall et al., 2021; Title et al., 2024).

9 Future Directions and Emerging Technologies

9.1 Application of genomic and transcriptomic tools in sensory evolution research

Sequencing technology is getting more advanced. Scientists use these tools to study snakes' genes and transcriptomes, which is how the genes in their bodies work. Through these studies, people have a clearer understanding of how snakes' senses evolved step by step. Some large-scale analyses have found that some genes and regulatory regions have undergone specific changes. These changes are related to sensing heat, seeing things, bone structure, and digestion (Peng et al., 2023) (Figure 2). These findings tell us why snakes are different from other animals in terms of sense. These technologies are also used in the study of snake venom. Studies have found that the diversity of snake venom may be because some genes have been copied or some genes have new functions later. This makes snake venom more complex and more suitable for different hunting methods. As genetic technology and computer analysis methods become better and better, scientists may be able to find out which type of molecules are behind the sensory abilities of snakes in the future (Rao et al., 2022).

9.2 Neuroecological research and brain imaging technology

Neuroecology is a method that combines behavior and neuroscience. It can help us understand how the snake brain processes various sensations. Although most of the research is still focused on the genetic level, research on snake brains is also slowly advancing. For example, some people use artificial neural networks to simulate the spinal cord of snakes. This method is also used to make robot snakes so that they can imitate the movements of real snakes (Fadelli, 2020). These studies have opened up new ideas for us and made it easier for us to understand how the senses and movements of snakes are coordinated. In the future, if brain imaging technology and equipment for recording neural activity continue to improve, maybe we can really "see" how the snake's brain reacts. In this way, we can better understand how the snake's brain actually processes various sensory information.

9.3 Application of snake sensory biology in the field of bionics and robotics

Snakes have very sensitive sensory systems, and their flexible movement methods provide a lot of inspiration for the design of bionic robots. Now scientists have made "soft snake robots", which refer to a neural rhythmic system called "central pattern generator (CPG)" in snakes, and also add sensory feedback functions. These robots can crawl freely and turn flexibly in complex terrain (Liu et al., 2023; 2025). In addition, scientists have also developed "electronic skin" that can sense pressure by imitating the tactile receptors of snakes. This skin is very sensitive and can feel contact and pain. It can be used on robots to help them sense danger and environmental changes (Zheng et al., 2022). These "snake robots" can not only be used in medical, rescue, detection and other scenarios, but also promote the combination of neuroscience and engineering technology, opening up more new interdisciplinary directions (Pettersen, 2017).

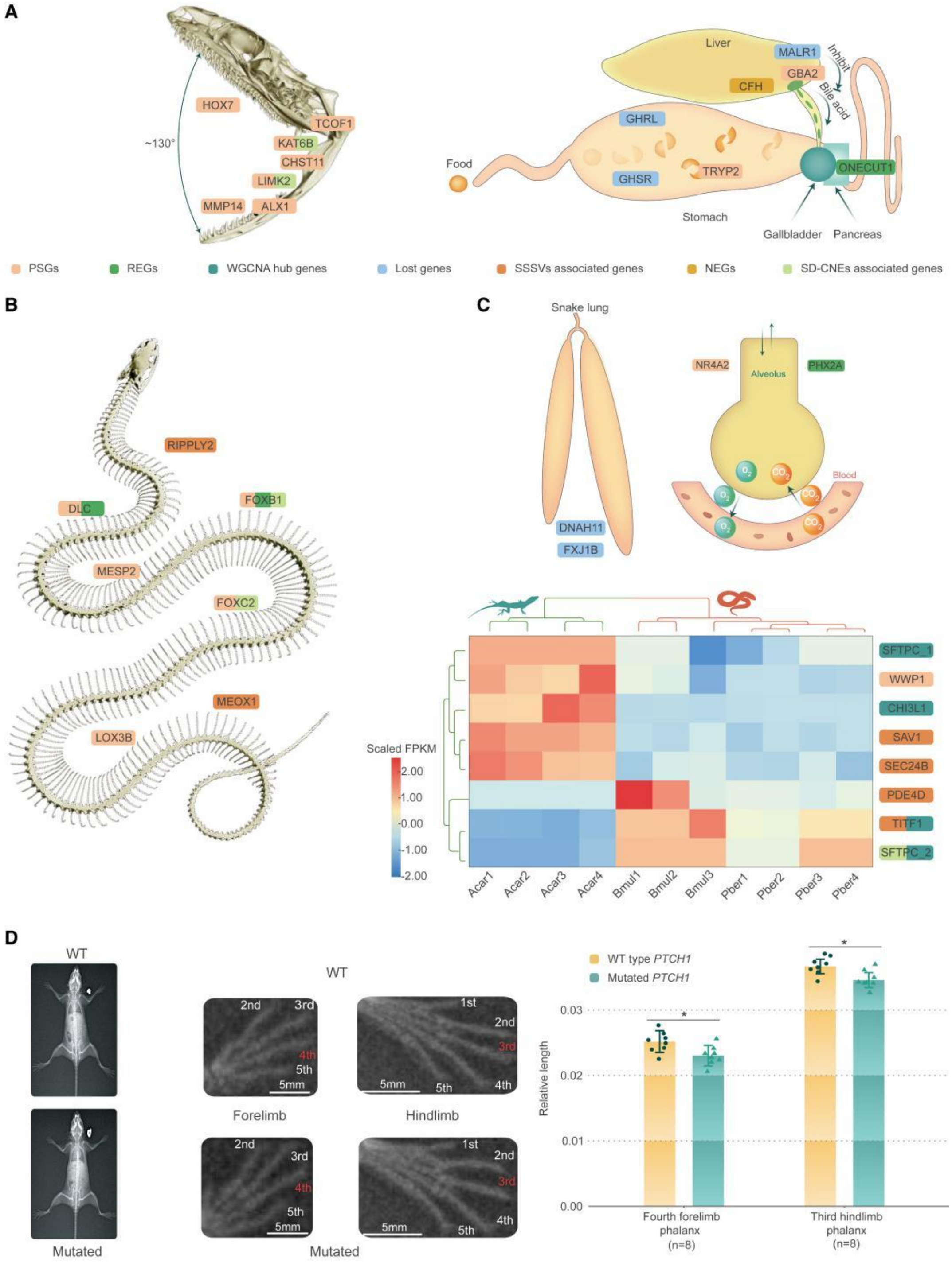

Figure 2 Genetic basis of skeletal system evolution and organ adaptation in snakes (Adopted from Peng et al., 2023)

10 Conclusion

Snakes' sensory systems have become increasingly diverse and sophisticated over the course of their evolution. These senses allow snakes to adapt to a wide variety of environments. From forests to deserts, underground to water, they are almost everywhere. This article focuses on the three most important senses: infrared, chemical, and mechanical. They allow snakes to survive in a variety of environments. For example, infrared perception is most evident in pit vipers, pythons, and some anacondas. These snakes have special "fossa organs" that can sense subtle changes in temperature, allowing them to accurately locate and attack warm-blooded animals even in the dark. This is their unique hunting technique. Chemical perception is also a specialty of snakes. Snakes use their tongues to bring odors from the air back to their mouths, and use their vomeronasal organs to analyze this chemical information. This helps them track prey, find mates, and avoid predators. Whether they live on the ground or in the water, this "olfactory system" is very useful.

Snakes also have strong mechanical perception. The scales on their heads can sense pressure and vibrations. This ability is especially important in water, for example, sea snakes rely on it to respond to water flow and other touch signals. Snakes with different lifestyles also have their own adaptations in vision and hearing. For example, burrowing snakes have poor eyesight, but can clearly feel ground vibrations; snakes that are active during the day and like to climb trees usually have better vision.

These sensory systems do not work alone, they often work together. In some environments with poor light, such as caves or at night, snakes will rely more on infrared perception and chemical perception. Mechanical feedback also helps them sense body movements and directions. Multiple senses work together to allow snakes to survive well under the most unfavorable conditions. It can be said that the evolution of snakes' sensory systems is closely related to their lifestyles. These flexible ways of perception allow them to spread to almost all types of ecological environments. Whether in forests, deserts, oceans or underground, snakes can find their own way to survive. These changes in senses not only represent the mutual influence of their body structure and function, but also allow us to see their various behaviors in the ecology, such as how to hunt, how to choose habitats, and how to deal with other animals.

Studying the evolution and integration of these senses not only helps us understand snakes, but also how vertebrates as a whole adapt to their environments and form different ecological niches. As we continue to delve deeper into the genetic and neural mechanisms of snakes, we will also have a clearer understanding of the forces that have driven this extremely diverse reptile lineage to where it is today.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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