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How do some fungi turn insects into zombies?

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Abstract

UPPER READING LEVEL

Did you know that certain fungi can turn insects into zombies, just like in the movies? These "zombie-making" fungi control the insects' behavior and make their hosts do strange things like walking a long way, climbing tall plants, and hanging onto high surfaces. This is so the fungi can make their infectious spores spread further. There are many types of zombie-making fungi, and most have evolved independently.

Yet they change the insects' behavior in a similar way. How do they do this and why is it so common?

We reviewed previous studies on zombie-making fungi to search for an answer. These fungi use both mechanical and chemical processes to control their hosts. And while the changed behavior is very similar, the ways they achieve it vary greatly among the different species of zombie-making fungi. Each one has its own unique way of manipulating insects to change the same behaviors! We believe these same behaviors are changed by all these different fungal species because these manipulations are the best way to infect as many other hosts as possible.

Introduction

Have you ever watched a zombie movie? In some of them, zombies are dead things that come back to life, but in others, zombies are caused by a virus, or a bacteria, or even a fungus that changes people's behavior. While these movies can be terrifying, dead things cannot come back to life. But did you know that behavior-manipulating microbes actually exist in Nature?

Zombie fungi are one of the greatest examples, and, thankfully, the **hosts** are not people but insects. Like all infectious diseases, these zombie-making fungi want to spread. Insects are small, so it's difficult for the fungi to spread with their infectious **spores**. So, the **pathogens** hijack the insects' behavior to spread their spores more efficiently! For example, the fungus *Entomophthora muscae* infects flies and makes them climb and glue themselves to vegetation by making their saliva extra sticky. Once the fly is stuck, the fungus kills its host and starts to make spores. This high position helps these spores spread far using the wind.

The wasp is stuck to the leaf as the fungus grows from its body. **Photo:** Roel Fleuren

There are millions of fungal species that can infect insects. Some fungi kill their insect hosts quickly without manipulating their behavior. But zombie-making fungi have a more specialized relationship with their hosts. They spend more time living in **symbiosis** with their hosts before eventually killing them. And there are a lot more of these fungi than we previously thought!

It's fascinating that zombie-making fungi have evolved independently! Each species has co-evolved closely with its insect host over millions of years and developed its own strategy of host manipulation. Sometimes the fungi evolve more quickly and are better able to infect their hosts, and sometimes the hosts evolve more quickly and are better able to fight off the infections. In the end, the fitter populations of both hosts and fungi 'win' the competition! But even though these fungi have co-evolved with different insect hosts, they induce similar behavior changes. These include altered **locomotion**, new climbing behaviors, and attraction to different **abiotic factors**. But what about the **mechanisms** behind these manipulation strategies? Are they also the same among the different species or unique? And why is infecting insects a common strategy among fungi? This is what we wanted to find out.

Methods

We reviewed previous studies on zombie-making fungi. We combined all their findings on the behavioral manipulation of insect hosts. We looked specifically at two factors:

- the mechanisms behind these behaviors, and
- the evolutionary reasons why they might be so common.

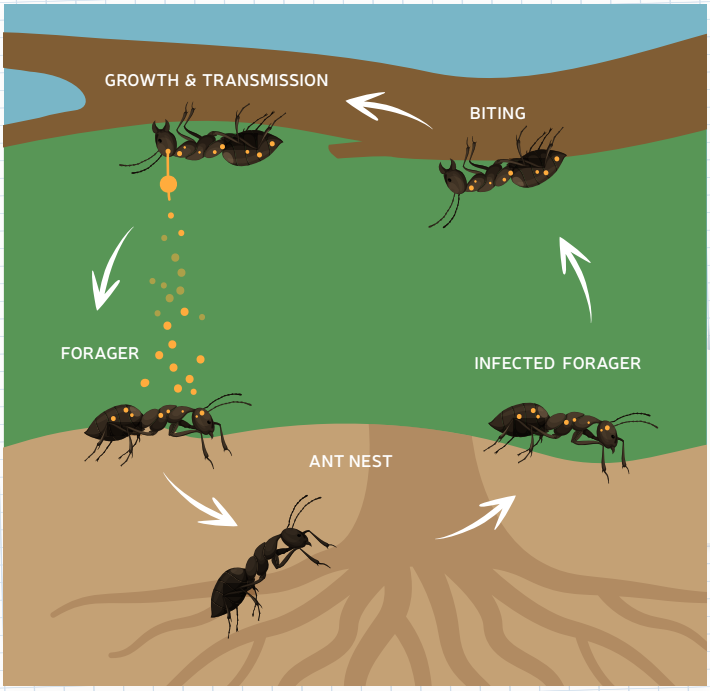

Figure 1:
Transmission cycle of a zombie-making fungus (*Ophiocordyceps unilateralis*) that infects ants.

Results

Zombie-making fungi have developed remarkable ways to control insects (see fungus-host examples in Table 1 on the next page). These include:

- increased movement – the hosts go to places that are more favorable for spreading spores.
- light seeking – zombie making fungi use light cues to start certain behavior manipulation, and may use light as a guide to direct climbing behavior.
- climbing (also called **summiting**) – the higher the host, the easier it is for the spores to spread.
- adherence to surface (also called **biting behavior** and "death grip") – after the insect has climbed up the plant, it bites onto it to secure its position.
- splayed wings – so that the wings don't get in the way of spore dispersal.
- increased sexual behavior – the insect infects others through direct contact.
- circadian rhythm changes – insects stay awake when they would usually be sleeping, and behavioral changes happen at specific times of the day.

After infecting the host, the fungi manipulate their hosts' behavior. The pathogens achieve this through mechanical and chemical processes.

- Mechanical processes involve physical changes. One example is the induced splaying of wings. This is common among various fungal species, but they achieve this through various routes. Other processes are unique, such as the destruction of reproductive organs by *Massospora* fungi.
- Chemical manipulation involves the secretion of biomolecules. They can directly affect the insect's brain or nervous system. For example, alkaloid compounds, a class of a powerful narcotic drugs that include adrenaline and morphine, are made by the fungi that infect cicadas and ants. They can also indirectly change the host's behavior by changing its internal state. Some fungi cause the insect to starve, which of course changes its behavior. Previous studies have found many different biomolecules released by various zombie-making fungi.

Climbing, or summiting behavior, is quite common among manipulated insects. Why do you think that is?

Behavior	Host	Parasitic fungus genus
Increased movement	Ants	*Ophiocordyceps*
Climbing (summiting)	Flies	*Entomophthora*
	Ants	*Ophiocordyceps*
	Grasshoppers	*Entomophaga*
Light seeking	Ants	*Ophiocordyceps*
Adherence to surface	Flies	*Entomophthora*
	Ants	*Pandora*
Increased sexual behavior	Cicadas	*Massospora*
Splayed wings	Flies	*Entomophthora*
	Soldier beetles	*Eryniopsis*

Table 1. Behaviors in insect hosts manipulated by zombie-making fungi.

Discussion

We see similar manipulated behaviors in various insect hosts. Yet the mechanisms behind them are diverse. So why do these behaviors happen so often? One possibility is that the fungi target the easiest behaviors to change. Animals, including insects, change their behavior when their environment changes. Zombie-making fungi take advantage of this and manipulate the insects' behavior. It's as if the fungi have found a way to hack the insects' brains and make them do what is best for themselves instead.

Another possible reason for these similar behaviors is that they help the fungi spread to new hosts. Making the insects do certain things, like climbing, increases the pathogen's chances of spreading.

Some of the behaviors can help the fungi live longer by avoiding the hosts' social immune responses. Ants infected with *Ophiocordyceps* are made to wander away from the colony. Otherwise, the other ants might sense the infection and kill the sick host before the fungus has time to spread. Moreover, the host's immune and nervous systems are connected. When insects get sick, the immune system releases substances that affect their behavior. The fungi can take advantage of this as well! It is like using the insects' own immune system against them.

Conclusion

Zombie-making fungi are extraordinary organisms. They have evolved unique strategies to infect and control insects. Their ability to manipulate host behavior is a testament to the wonders of Nature. It also highlights how intricate the relationships between different organisms in ecosystems are. Everyone's actions, including ours, can have significant consequences on other living beings! This is why our choices should have positive impacts on the environment. We should reduce our waste, conserve resources, and support conservation efforts.

Glossary of Key Terms

Abiotic factors - non-living conditions in the environment. For example, temperature, light, water, air, etc.

Biting behavior - the infected (by zombie-making fungus) insect bites onto a surface, such as a plant, and secures its position. Thus, the insect is unable to fall from favorable locations for spore dispersal.

Host - in a parasitic-host relationship, the term "host" refers to the organism that is exploited by the other organism – the parasite. The relationship is always beneficial for the parasite and negative for the host. For example, the parasitic fungi of the genus *Ophiocordyceps* uses ants as hosts.

Locomotion - the act of moving (traveling) from one place to another. It can be achieved by various modes, such as walking, running, swimming, etc.

Mechanisms (of behavior manipulation) - zombie-making fungi use various methods to control their hosts' behavior. These include mechanical and chemical processes. The mechanical processes involve physical changes – the fungus penetrates the insects' exoskeleton, then the nervous system. Chemical processes include the release of bioactive compounds, like proteins, alkaloids, etc. These chemicals alter the insects' behavior, much like drugs and alcohol can alter ours. Mechanical and chemical processes usually act together, not on their own.

Pathogen - a microorganism (or virus), such as bacterium, fungus, or parasite, that can cause disease in living organisms. You can think of them as microscopic parasites.

Spores - unlike bacterial spores, which are very resistant and primarily involved in survival, fungal spores are reproductive, like the seeds of a plant. Fungi produce them in large numbers, and they disperse over long distances to colonize new habitats. In the case of fungal pathogens, these habitats are new hosts.

Summiting - infected insects (by zombie-making fungi) climb to high locations, such as the tops of plants. It's part of the fungi's strategy to enhance spore dispersal.

Symbiosis - close and somewhat long-term relationship between two different species. It can be beneficial, neutral, or harmful.

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Check your understanding

1 What are some common behaviors induced by zombie-making fungi in insects?

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2 What have zombie-making fungi evolved to achieve when they manipulate the insects' behavior?

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3 Behavior manipulation is a form of adaptation. Can you think of other examples in Nature?

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4 Zombie-making fungi and insects have a parasite-host relationship. Can you think of other parasite-host relationships?

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5 There is a fictional TV series and video game where a zombie-making fungus, *Cordyceps*, mutates to infect humans turning them into "zombies". Why is this impossible?