Physicists eye neural fly data, find formula for Zipf's law

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The Zipf's law mechanism was verified with neural data of blowflies reacting to changes in visual signals.

Physicists have identified a mechanism that may help explain Zipf's law – a unique pattern of behavior found in disparate systems, including complex biological ones. The journal *Physical Review Letters* is publishing their mathematical models, which demonstrate how Zipf's law naturally arises when a sufficient number of units react to a hidden variable in a system.

"We've discovered a method that produces Zipf's law without fine-tuning and with very few assumptions," says Ilya Nemenman, a biophysicist at Emory University and one of the authors of the research.

The paper's co-authors include biophysicists David Schwab of Princeton and Pankaj Mehta of Boston University. "I don't think any one of us would have made this insight alone," Nemenman says. "We were trying to solve an unrelated problem when we hit upon it. It was serendipity and the combination of all our varied experience and knowledge."

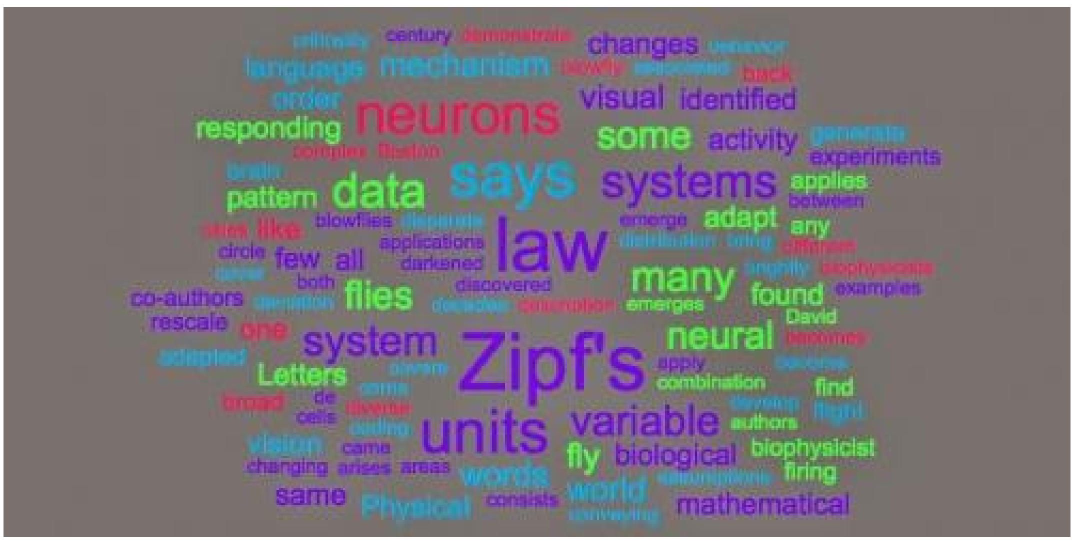
Their findings, verified with neural data of blowflies reacting to changes in visual signals, may have universal applications. "It's a simple mechanism," Nemenman says. "If a system has some hidden variable, and many units, such as 40 or 50 neurons, are adapted and responding to the variable, then Zipf's law will kick in."

That insight could aid in the understanding of how biological systems process stimuli. For instance, in order to pinpoint a malfunction in neural activity, it would be useful to know what data recorded from a normally functioning brain would be expected to look like. "If you observed a deviation from the Zipf's law mechanism that we've identified, that would likely be a good place to investigate," Nemenman says.

Zipf's law is a mysterious mathematical principle that was noticed as far back as the 19th century, but was named for 20th-century linguist George Zipf. He found that if you rank words in a language in order of their popularity, a strange pattern emerges: The most popular word is used twice as often as the second most popular, and three times as much as the third-ranked word, and so on. This same rank vs. frequency rule was also found to apply to many other social systems, including income distribution among individuals and the size of cities, with a few exceptions.

More recently, laboratory experiments suggest that Zipf's power-law structure also applies to a range of natural systems, from the protein sequences of immune receptors in cells to the intensity of solar flares from the sun.

"It's interesting when you see the same phenomenon in systems that are so diverse. It makes you wonder," Nemenman says.



The physicists are now researching whether they can bring their work full circle, by showing that the mechanism they identified applies to Zipf’s law in language.

Scientists have pondered the mystery of Zipf's law for decades. Some studies have managed to reveal how a feature of a particular system makes it Zipfian, while others have come up with broad mechanisms that generate similar power laws but need some fine-tuning to generate the exact Zipf's law.

"Our method is the only one that I know of that covers both of these areas," Nemenman says. "It's broad enough to cover many different systems and you don't have to fine tune it: It doesn't require you to set some parameters at exactly the right value."

The blowfly data came from experiments led by biophysicist Rob de Ruyter that Nemenman worked on as a graduate student. Flies were turned on a rotor as they watched the world go by, hundreds of times. The moving scenes that the flies repeatedly experienced simulated their natural flight patterns.

The researchers recorded when neurons associated with vision spiked, or fired. All sets of the data largely matched within a few hundred microseconds, showing that the flies' neurons were not randomly spiking, but instead operating like precise coding machines.

If you think of a neuron firing as a "1" and a neuron not firing as a "0," then the neural activity can be thought of as words, made up of 1s and 0s. When these "words," or units, are strung together over time, they become "sentences."

The neurons are turning visual stimuli into units of information, Nemenman explains. "The data is a way for us to read the sentences the fly's vision neurons are conveying to the rest of the brain."

Nemenman and his co-authors took a fresh look at this fly data for the new paper in *Physical Review Letters*. "We were trying to understand if there is a relationship between ideas of universality, or criticality, in physical systems and neural examples of how animals learn," he says.

In order to navigate in flight, the flies' visual neurons adapt to changes in the visual signal, such as velocity. When the world moves faster in front of a fly, these sensitive neurons adapt and rescale. These adaptions enable the flies to adjust to new environments, just as our own eyes adapt and rescale when we move from a darkened theater to a brightly lit room.

"We showed mathematically that the system becomes Zipfian when you're recording the activity of many units, such as neurons, and all of the units are responding to the same variable," Nemenman says. "The fact that Zipf's law will occur in a system with just 40 or 50 such units shows that biological units are in some sense special – they must be adapted to the outside world."

The researchers provide mathematical simulations to back up their theory. "Not only can we predict that Zipf's law is going to emerge in any system which consists of many units responding to variable outside signals," Nemenman says, "we can also tell you how many units you need to develop Zipf's law, given how variable the response is of a single unit."

They are now researching whether they can bring their work full circle, by showing that the mechanism they identified applies to Zipf's law in language.

"Letters and words in language are sequences that encode a description of something that is changing over time, like the plotline in a story," Nemenman says. "I expect to find a pattern similar to how vision neurons fire as a fly moves through the world and the scenery changes."

More information: Paper on *Arxiv*: arxiv.org/pdf/1310.0448.pdf

Provided by Emory University