

Order in Spontaneous Behavior

Delve into the surprising order found within the seemingly random behavior of fruit flies, revealing insights into brain function and the complexities of biological systems.

by Anton Pasternak



Background: What is Spontaneity?

Spontaneous Events

Events that are planned without official input or permits on purpose. Events that result from other events (for example, a victory celebration for a local sports team).

Spontaneous Movements

Every second several areas in the body are moving spontaneously. The pumping of the heart, the breathing and the peristaltic movement of stomach and intestines are all examples of this 'natural spontaneous movement'.

Spontaneous Behavior

The Oxford dictionary describes spontaneous behavior as:

“performed or occurring as a result of a **sudden** inner impulse or inclination and without **premeditation or external stimulus**.”

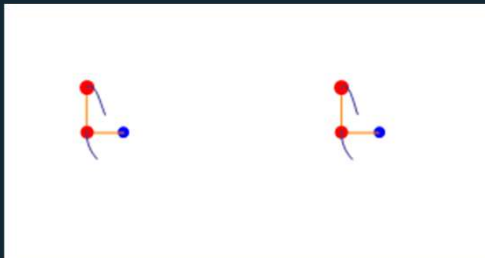
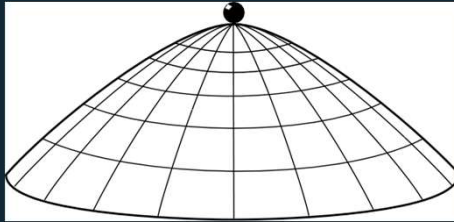
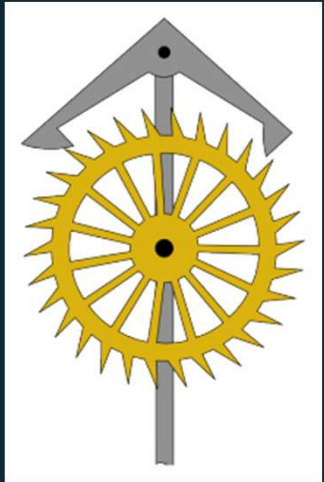
-“According to Laplace, randomness is only a measure of our ‘ignorance of the different causes involved in the production of events.’ “

Background: Deterministic vs Indeterministic Systems

Deterministic

Deterministic refers to systems or processes where the outcome is fully determined by the initial conditions and the rules governing the system. In a deterministic system, if you know the initial conditions and the rules, you can predict the outcome with certainty.

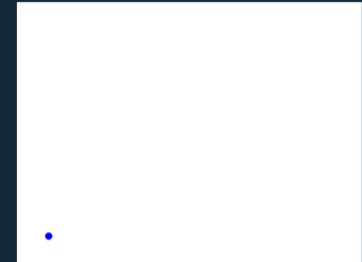
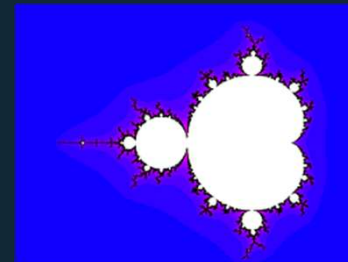
Predictability, consistency and absence of randomness,



Indeterministic

Indeterministic refers to processes or systems that do not follow a predictable, predetermined pattern and whose outcomes cannot be precisely determined in advance, even if the initial conditions are known. In other words, indeterministic systems exhibit behavior that appears random or unpredictable.

Unpredictability, randomness, chaos, lack of fixed rules, incomplete information, emergent behavior, non-linearity.



The Brain: A Traditional View In Neuroscience

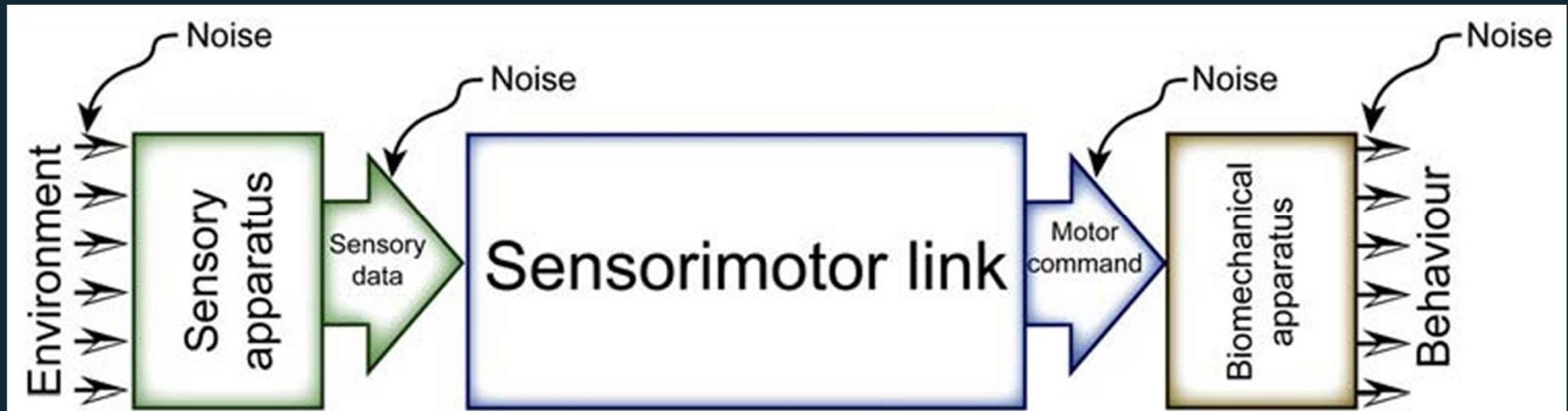
The Robot Hypothesis

-“Traditionally, brain function is viewed as **a deterministic input-output model**. However, this model fails to capture the intricate nuances and variations in behavior.”

Cause of Behavioral Variability

The real-world is dynamic, unpredictable and most of all **noisy**. Some claim that the behavioral variability of the brain results solely **from noise**.

–“According to the robot-hypothesis, there is an unambiguous mapping of sensory input to behavioral output. **If the behavioral output is not constant in a constant environment**, there are a number of possible **sources of noise, which would be responsible for the varying output.**”



The Brain: Competing Hypothesis

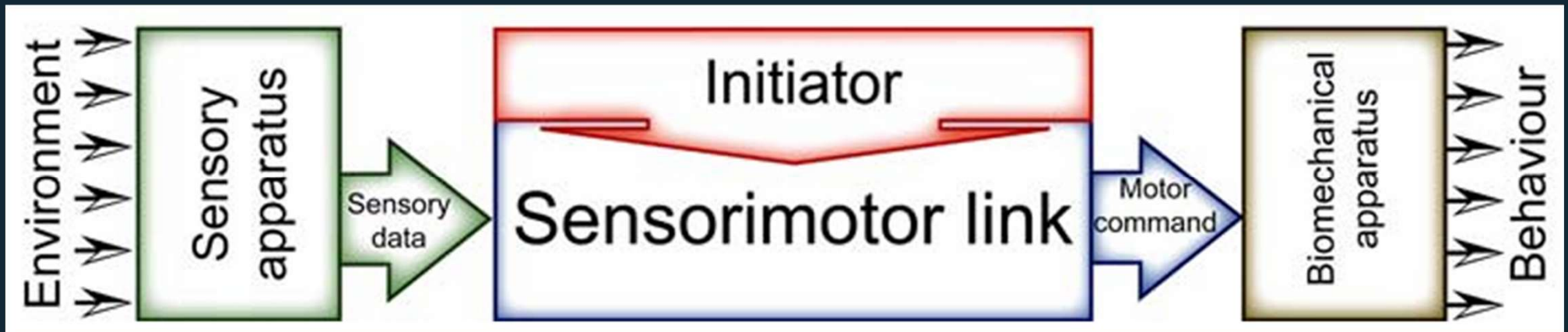
The Anti-Robot Hypothesis

-“Individual behavior is **fundamentally indeterministic** (not fundamentally deterministic but noisy) and precise prediction principally (not only technically) impossible.”

Cause of Behavioral Variability

Behavioral variety **comes from the inside** and not due to the noise of the outside world.

–“In a competing hypothesis, **non-constant output is generated intrinsically by an initiator of behavioral activity**. Note that the sources of noise have been omitted here merely because their contribution may be small, compared to that of the initiator, not because they are thought to be non-existent.”



Investigating the Spontaneity of the Behavior of Drosophila Fruit Flies



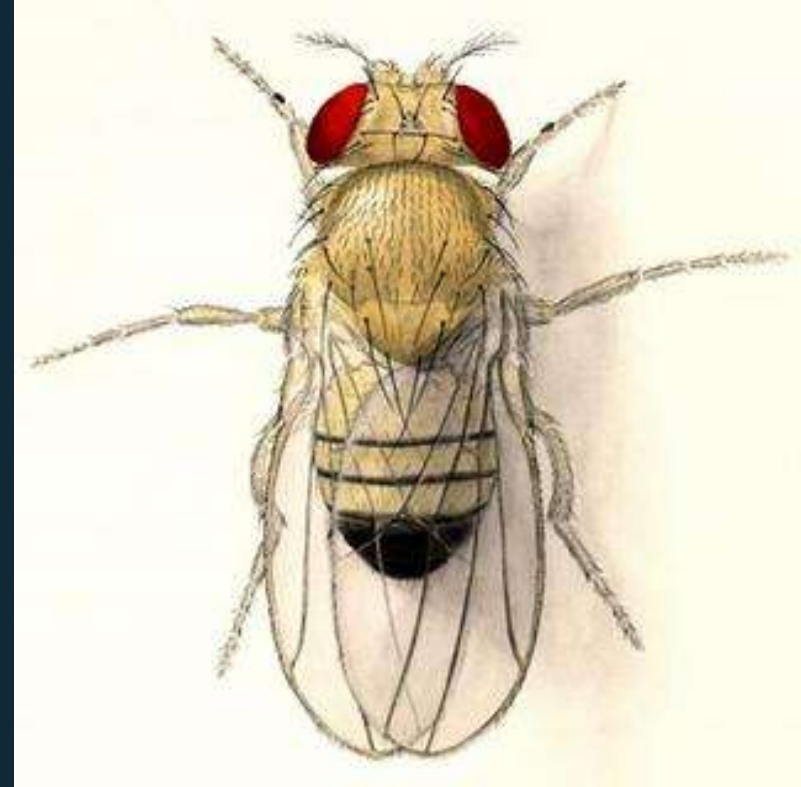
Subject

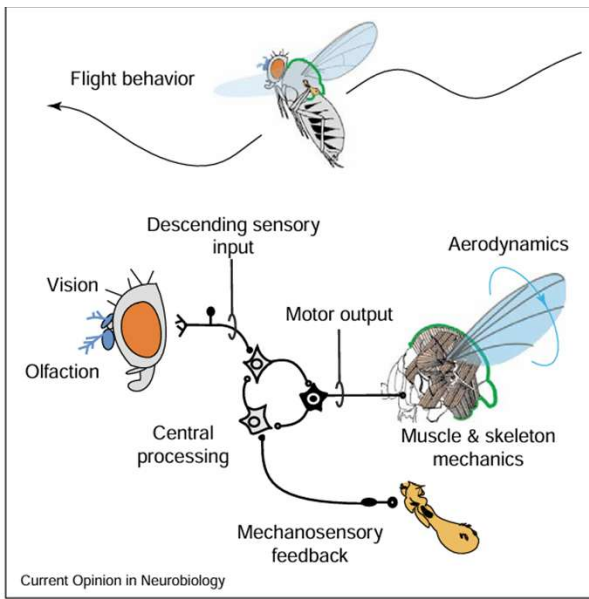
Tethered Drosophila fruit flies, offering controlled conditions to study their **spontaneous flight behavior**.



Objective

Uncover the underlying mechanisms driving behavioral variability. Determine whether it stems from **random noise or intrinsic adaptive traits**.





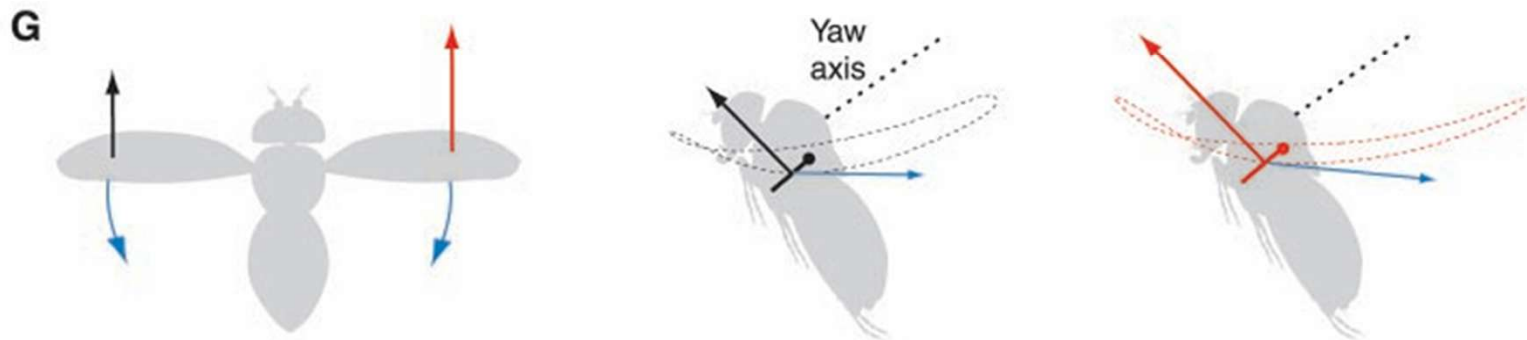
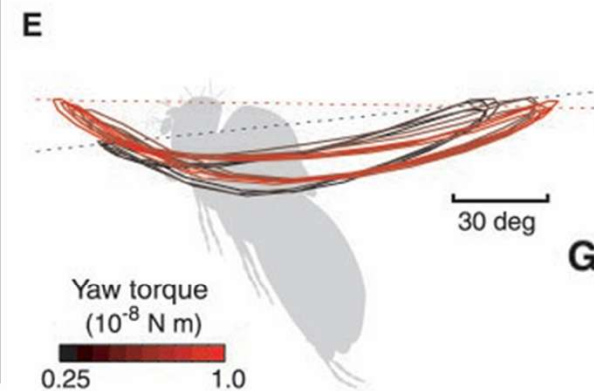
Experiment Design: measuring Torque Spikes



The **torque spikes** are sudden, rapid **changes in the rotational force** (torque) that flies generate during flight maneuvers. These spikes are crucial for quick turns and adjustments in flight direction. When a fly performs a rapid turn, its wings generate a burst of torque, causing a sharp change in its body orientation. **This allows the fly to quickly change direction** and avoid obstacles or capture prey

It is preceded by a **beat of the antenna** on the side **opposite** to the direction of the intended turn followed by **"steering" movements of the abdomen** and the **hind legs towards the side of the turn**.

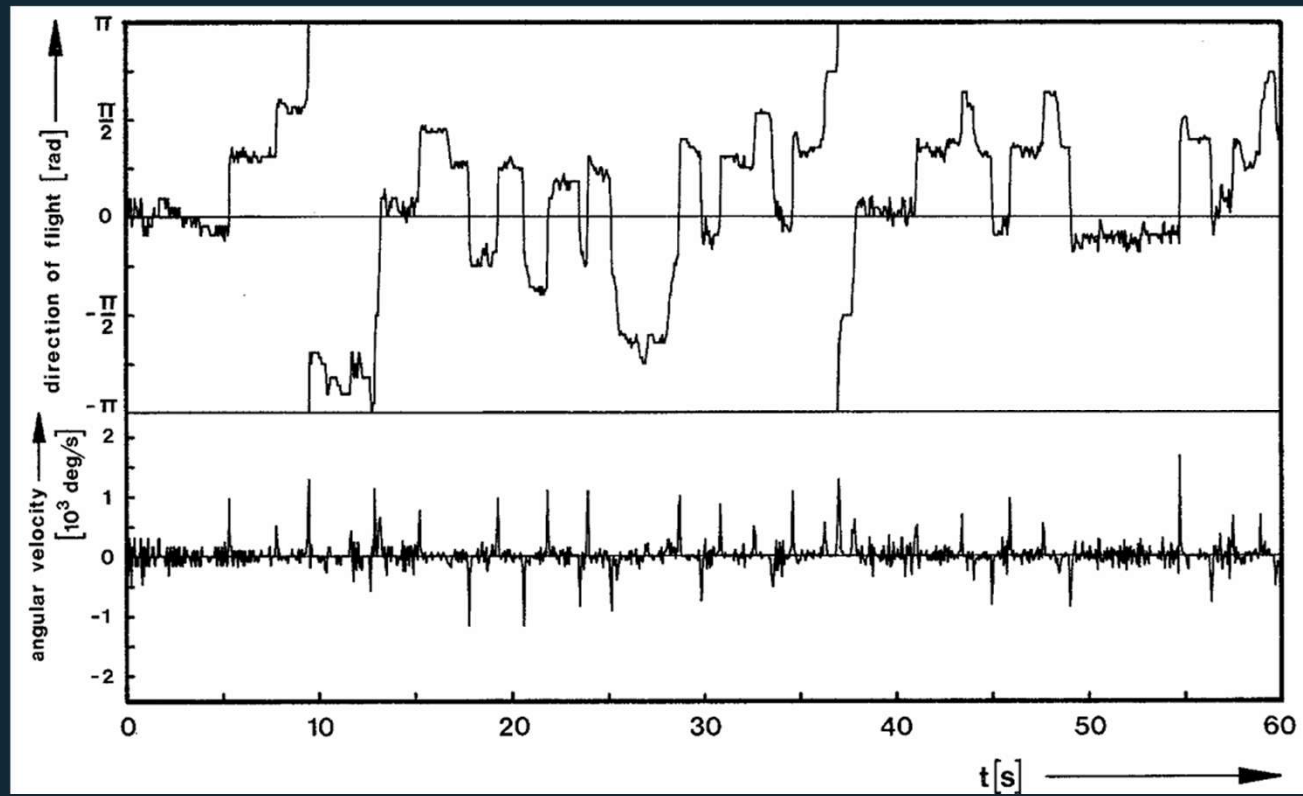
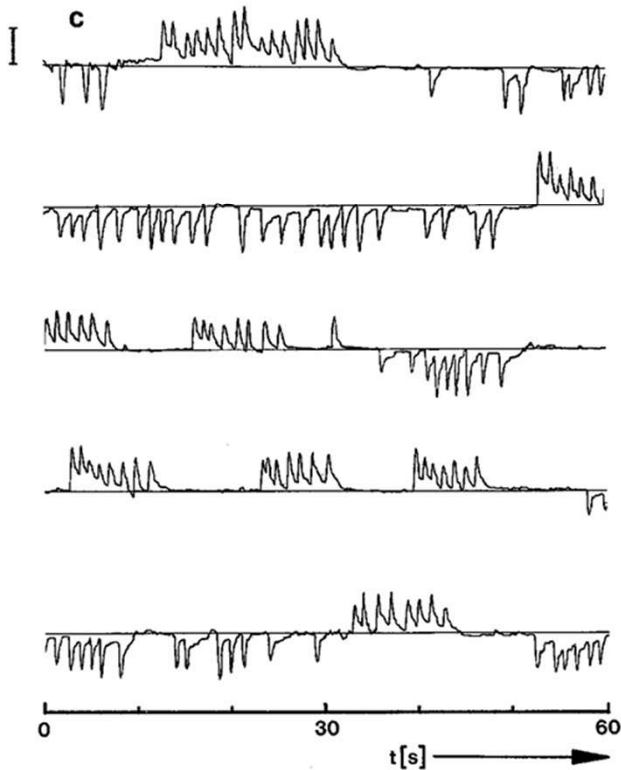
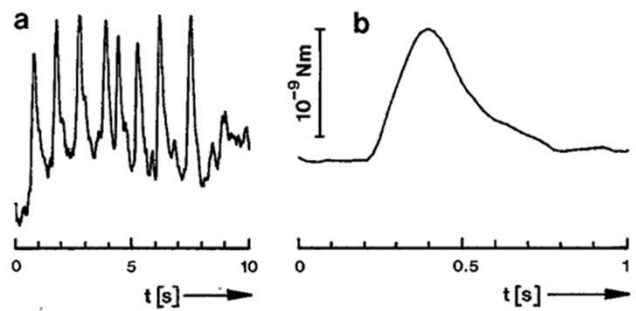
These latter transient changes of posture seem to occur in synchrony with the torque spike.





Experiment Design: measuring Torque Spikes

Why Torque Spikes?



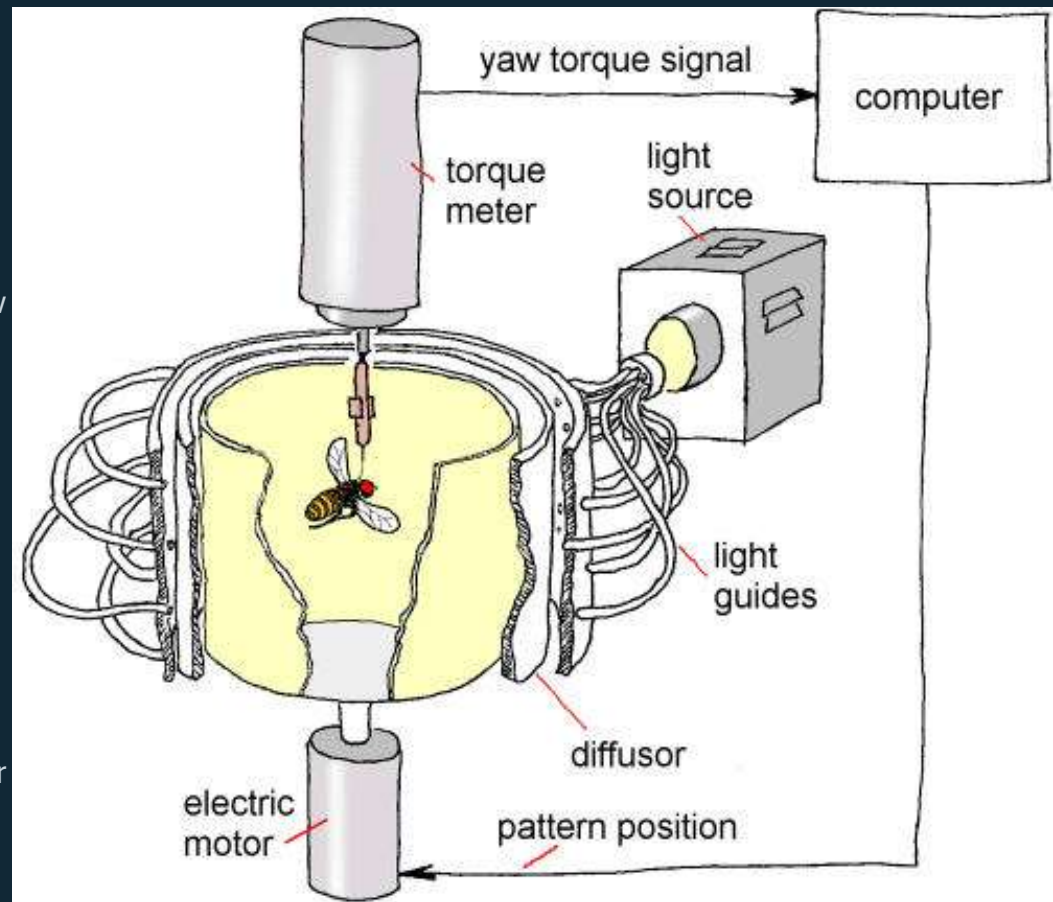
Experiment Design: Flight simulator set-up

The fly is **flying stationarily** in a cylindrical arena homogeneously illuminated from behind.

The fly's **tendency to perform left or right turns** (yaw torque) is measured continuously and **fed into the computer**. The computer in turn, **controls the rotation of the arena**.

An additional white screen (not shown) covered the arena from above for all groups.

Tethered flying *Drosophila* can beat its wings, move its abdomen, legs and proboscis, but cannot rotate or otherwise move



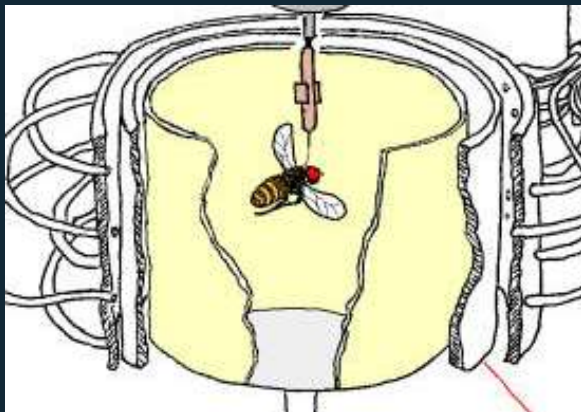
Experiment Design: Controlling the Environmental Input

39 flies were tested in a special environment they've built.

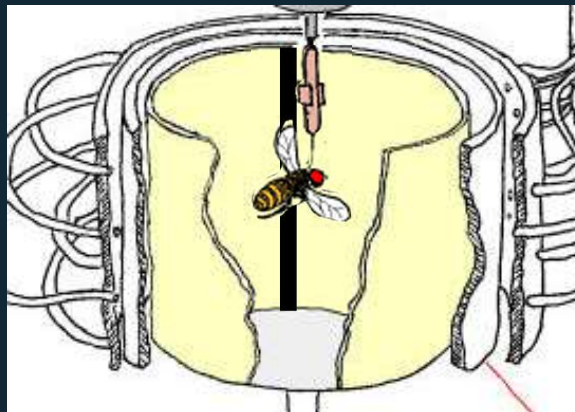
The environment **is kept so constant** (both between and within experiments), that **any remaining minute variation in it must be infinitely smaller** than any of the stimuli known to trigger turning behavior.

“A significant deviation from ideal randomness in any of these groups would contradict the ‘robot-hypothesis’.”

First group: “Open-loop”



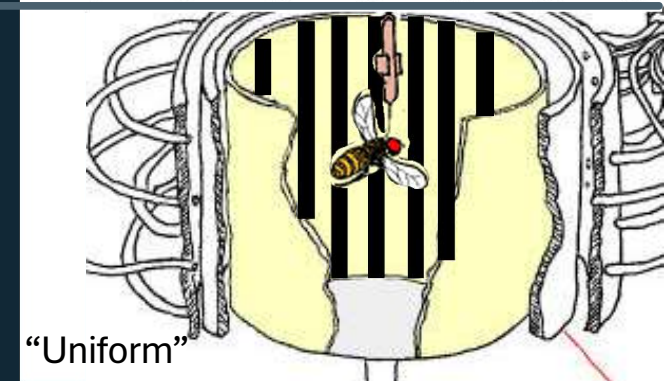
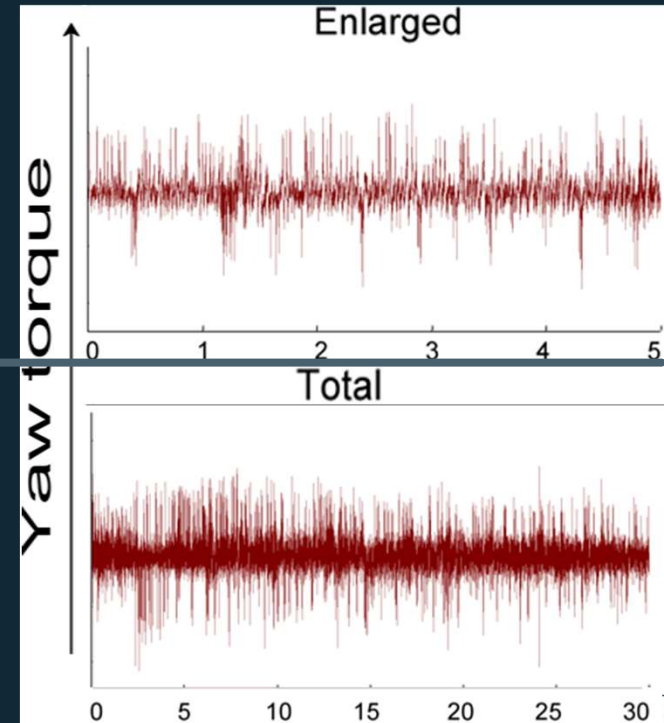
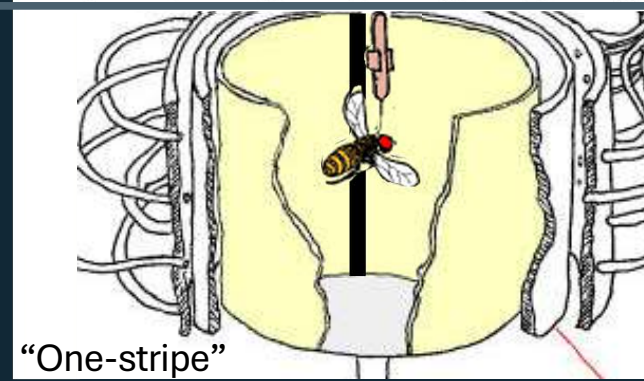
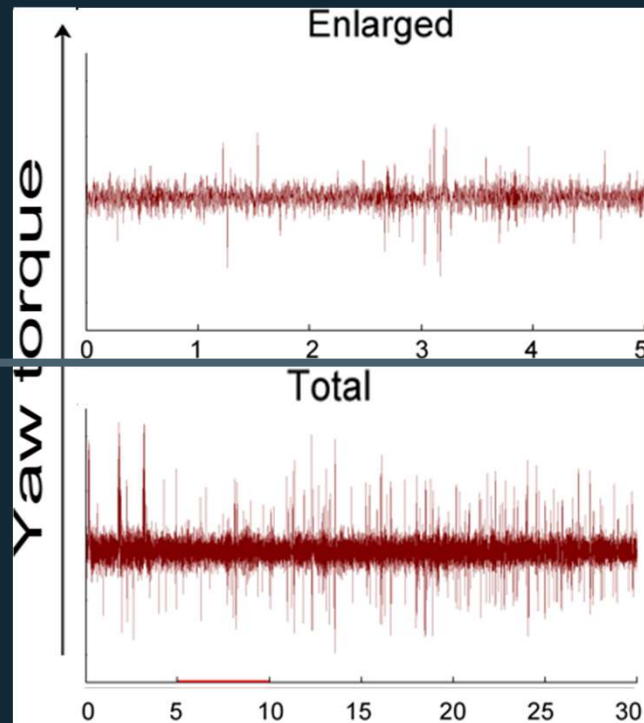
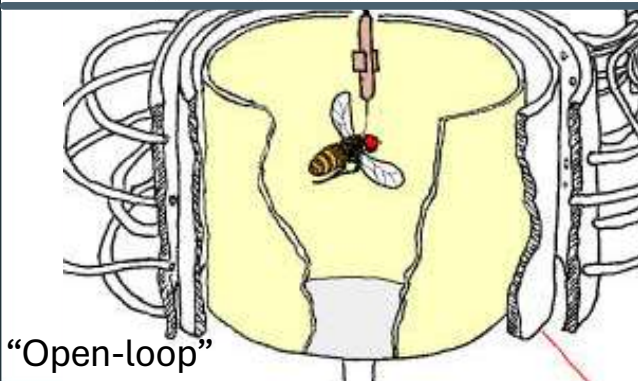
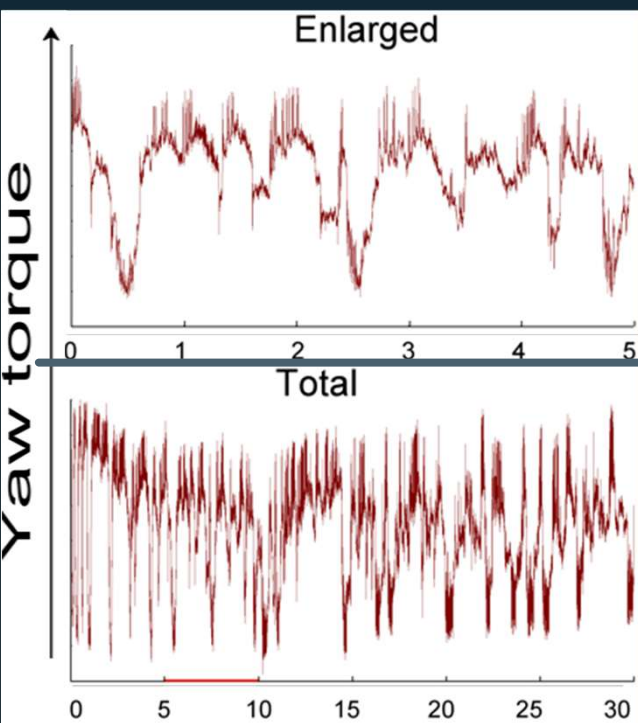
Second group: “One-stripe”



Third group: “Uniform”



Results



Results Analysis

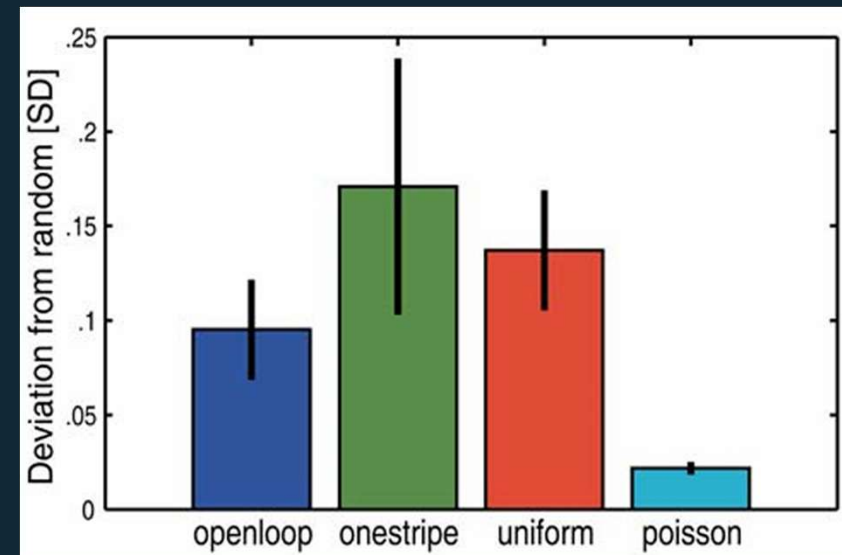
-“if the production of torque spikes in our featureless or uniform environment were due to random noise in the Drosophila brain or from any uncontrollable input, the time intervals between spikes (inter-spike interval, ISI) should reflect this stochasticity, much like the hiss of static from a radio between stations”

ISI Analysis

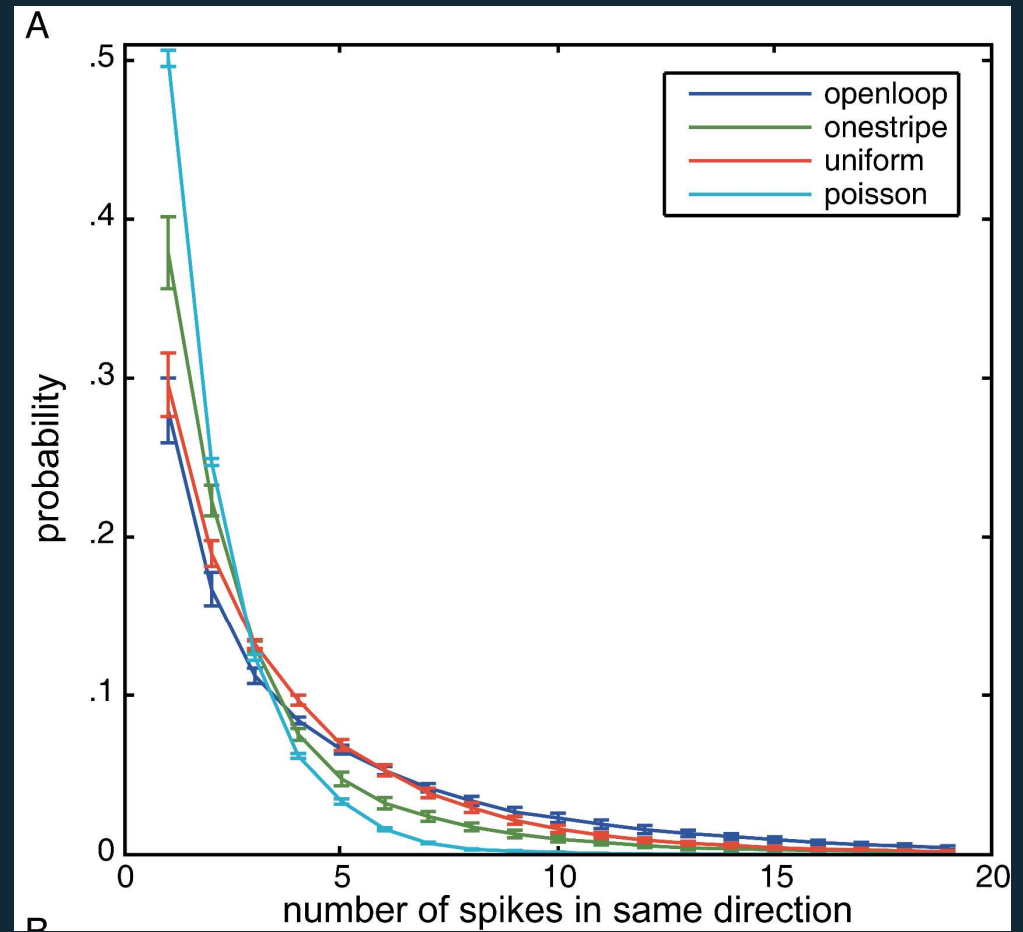
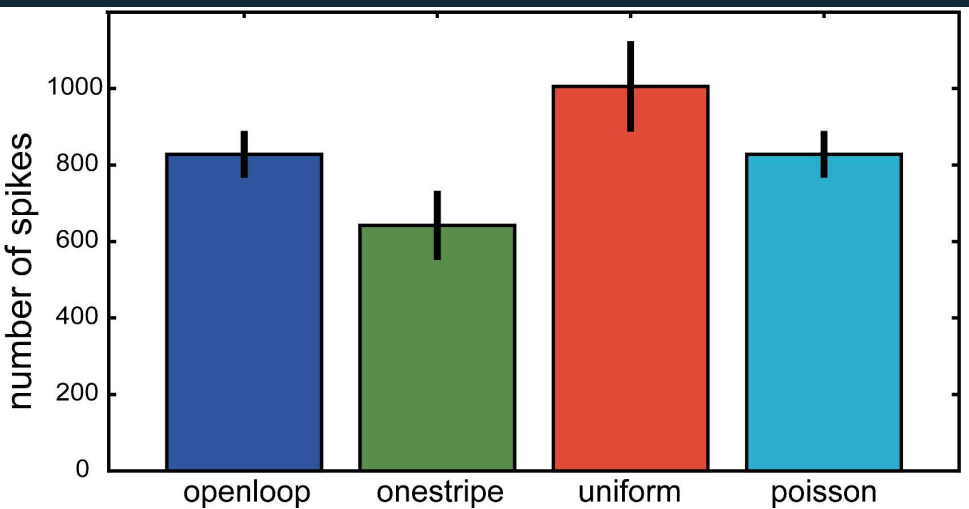
ISI analysis, a powerful tool for analyzing temporal patterns in behavioral data, was used to assess the timing and frequency of flight maneuvers.

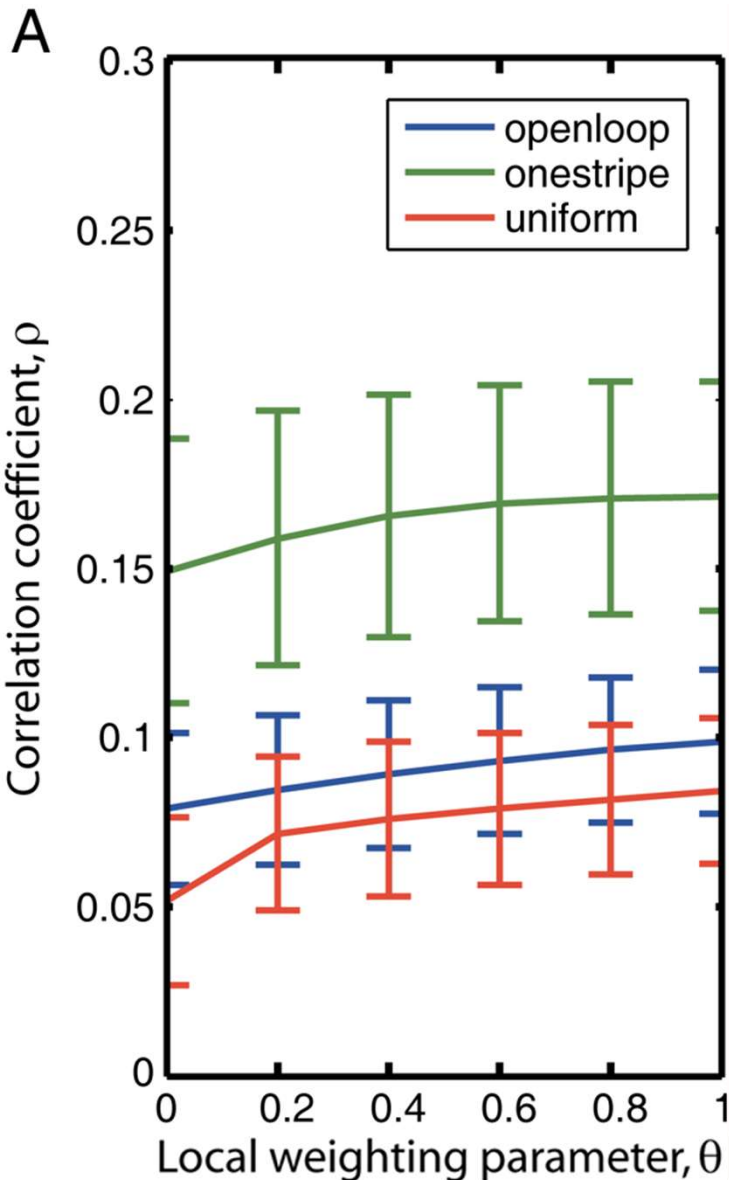
So, is it random?

-“Therefore, we adapted a recently developed computational method, **Geometric Random Inner Products (GRIP)**, to quantify the randomness of the ISI sequences of three groups of flies.”



Results Analysis





The Key to Behavioral Variability: Unstable Nonlinearity

Nonlinearity

The findings suggest that **nonlinear mechanisms**, which are characterized by complex interactions and feedback loops, are **crucial for generating behavioral variability**.

-“The tedious distinction between **random noise** and **unstable nonlinearity** is worthwhile, because the former points to **extrinsic origins** of variability, whereas the latter indicates **intrinsic origins**”

Translating the Results to English

1

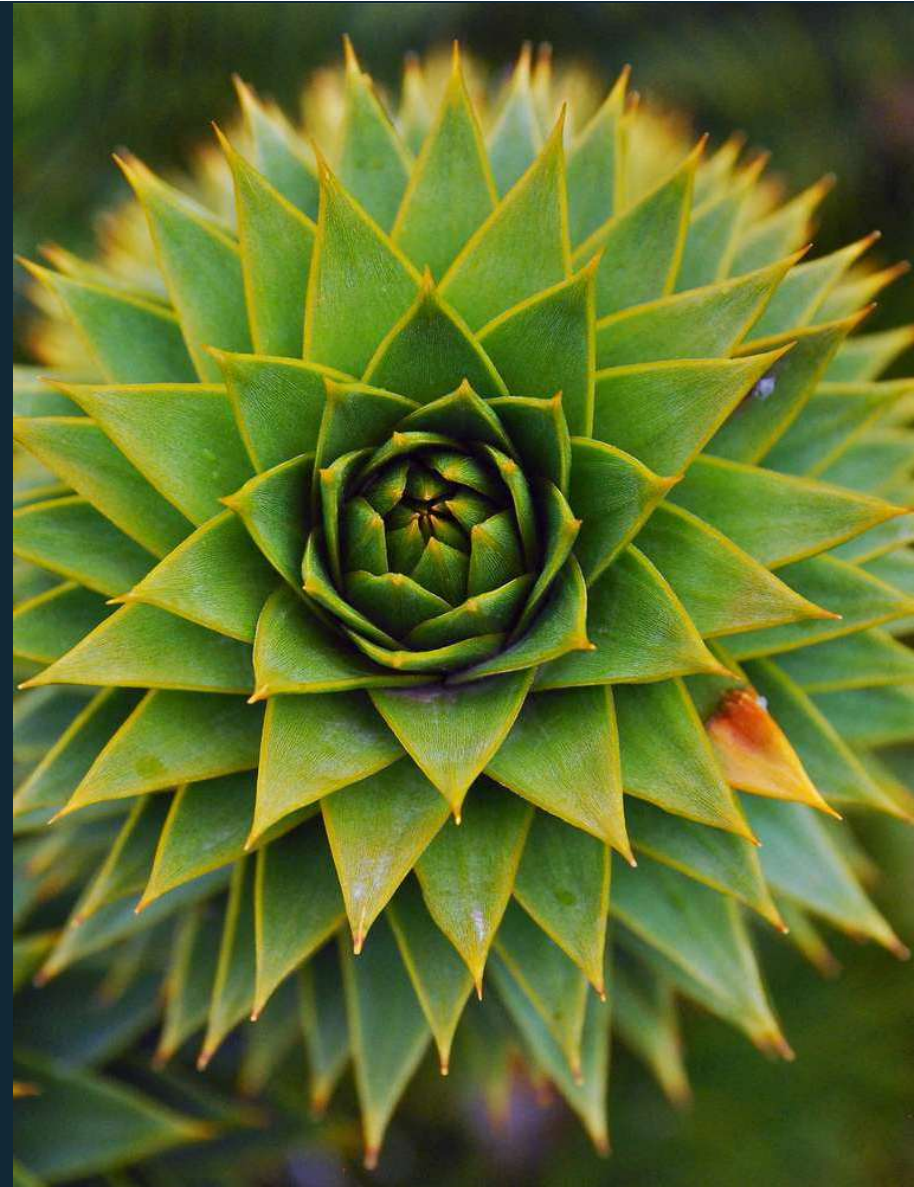
Endogenous Behavior

These findings suggest that behavioral variability is not just random noise but rather **a product of intrinsic, adaptive mechanisms within the brain.**

2

Fractal Order

The study revealed an unexpected level of order in the seemingly spontaneous flight maneuvers of fruit flies. This particular fractal order is called: **Levy flights**

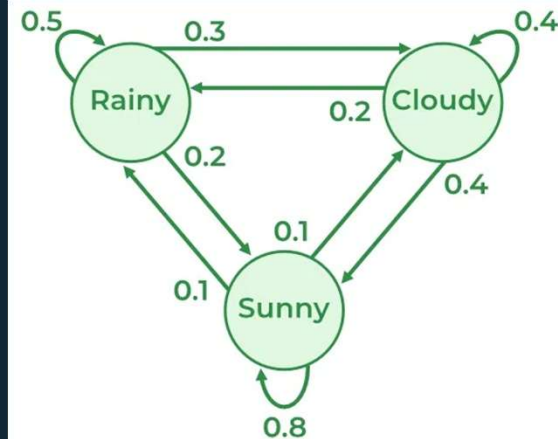
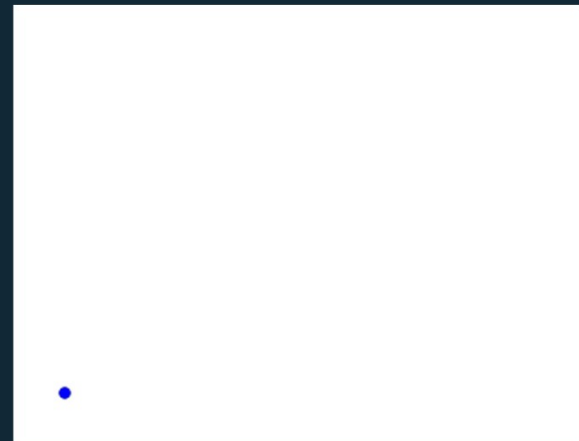


Lévy Flights

Lévy flights are a special class of Markov processes which are stochastic process describing a sequence of possible events in which the probability of each event depends only on the state attained in the previous event, AKA: "**What happens next depends only on the state of affairs now.**"

Levy flights model activities that involve **a lot of small steps, interspersed with occasional very large excursions.**

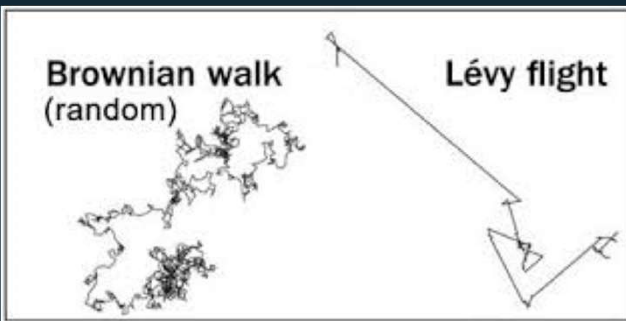
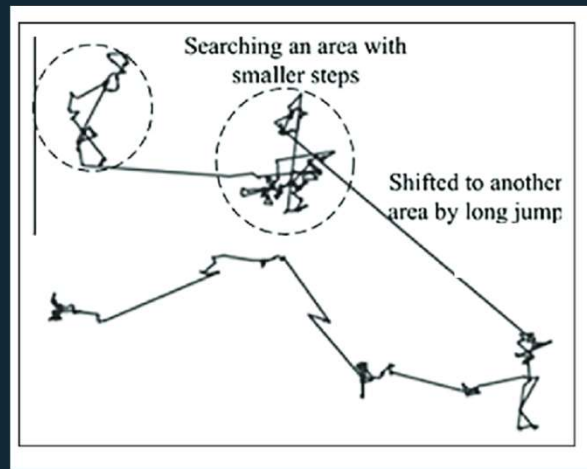
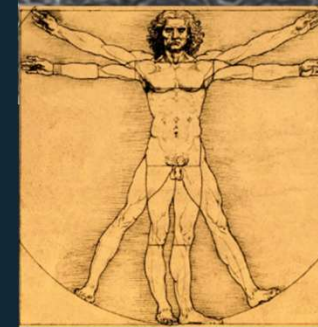
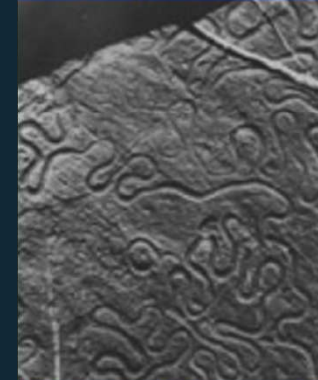
Foraging paths of Levy flights are fractal, matching the fractal distribution of food in complex ecosystems. This means animals develop **search strategies to avoid unproductive areas** by generating fractal stopping points, a property of Levy flights.



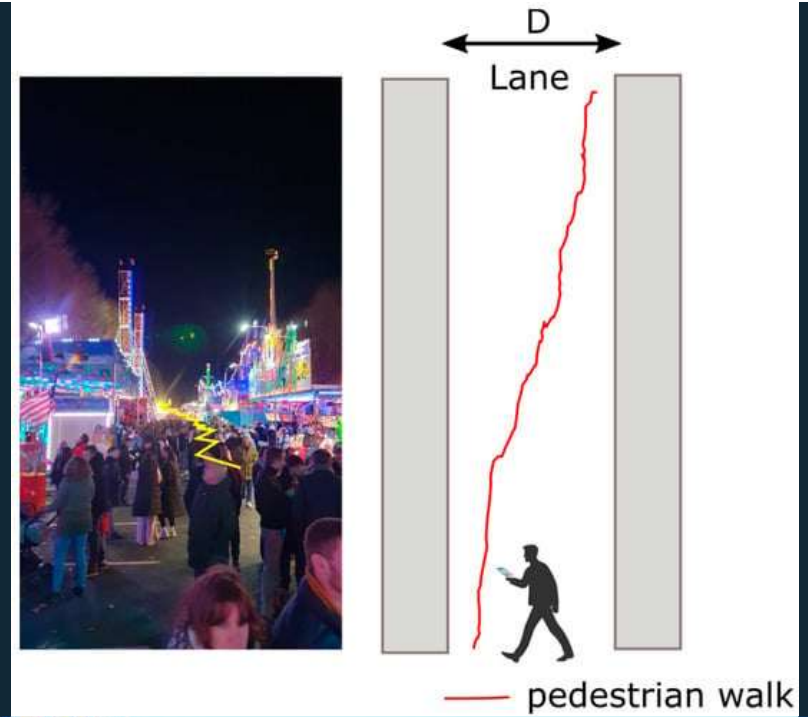
Lévy Flights are Everywhere

When sharks and other ocean predators cannot find food, they abandon Brownian motion, the random motion seen in swirling gas molecules, for Lévy flight — **a mix of long trajectories and short, random movements** found in turbulent fluids.

Researchers analyzed over 12 million movements recorded over 5,700 days in 55 data-logger-tagged animals from **14 ocean predator species in the Atlantic and Pacific Oceans**, including silky sharks, yellowfin tuna, blue marlin and swordfish. The data showed that **Lévy flights interspersed with Brownian motion can describe the animals' hunting patterns**.



Lévy Flights in Humans



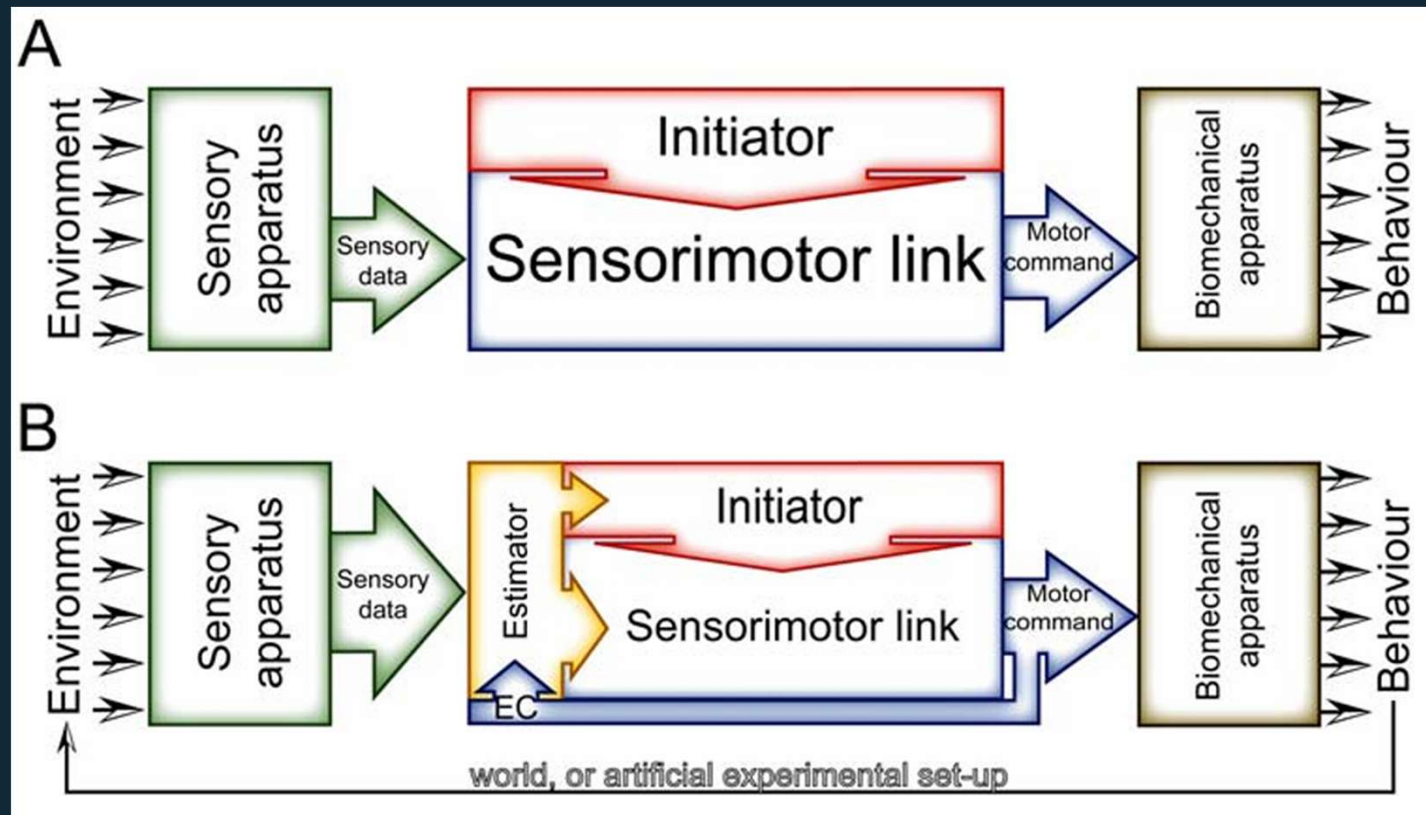
The Suggested Model

“In addition to the inevitable noise component, we detected a **nonlinear signature suggesting deterministic endogenous processes** (i.e., an initiator) involved in generating behavioral variability.”

This discovery suggests that the brain employs sophisticated internal mechanisms to generate variability in behavior, allowing for adaptation and flexibility.

“despite being largely deterministic, this initiator falsifies the notion of behavioral determinism”

“Even fly brains are more than just input/output systems”





Implications for Brain Function Models

1

New Insights

The research highlights the **importance of incorporating nonlinear mechanisms into brain function** models to better understand how behavior arises from neural activity.

-“future models of the brain may have to implement this or a related component for spontaneous behavior initiation, **if they strive to be biologically realistic**”

2

Future Directions

This discovery opens up exciting new avenues for research into the biological mechanisms behind the nonlinearity in brain.

-“Identifying the **neural circuitry housing the initiator** will be the logical next step in this research”



The Order Within Spontaneity

The findings challenge the traditional view of spontaneous behavior as purely random, revealing the hidden order and deterministic processes that govern the complexities of brain function.

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