

# Individual Variability of Neural Computations Underlying Flexible Decisions

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## 1 Introduction

Making flexible decisions is a key part of intelligent behavior. Whether it's dealing with social situations, reacting to a changing environment, or picking between different options, being able to adjust our thinking based on the situation is important. For years, scientists have been trying to figure out how the brain does this.

One big question is how the brain focuses on the important information and ignores distractions. Studies in both monkeys and rats show that decisions are made by adding up pieces of information over time. But even when animals perform the same task equally well, they might use different ways to do it inside their brains.

This kind of difference is important. Instead of assuming there's only one "correct" way the brain works, scientists now think there could be many strategies that all get the job done. Learning about this variability can help us build better artificial intelligence, create brain-computer interfaces, and understand how people differ in the way they think.

In neuroscience, some models help explain how the brain handles this flexibility. One popular idea is the line attractor model. It says that brain activity moves along a line as it adds up new information. Another idea is the selection vector, which helps the brain decide which information matters most, depending on the situation. These ideas have been important for understanding high-level thinking and control.

In this study, Pagan et al. explore how rats solve a flexible decision-making task. They used a task where rats had to pay attention to different features of sound, depending on the context. The researchers recorded brain activity and also built computer models (RNNs) to mimic the task. They found that different rats used different strategies, even though they all performed well.

These strategies could be explained by three main ideas: Direct Input Modulation (DIM), Indirect Input Modulation (IIM), and Selection Vector Modulation (SVM). Each rat used a mix of these methods to solve the task. The study expands on earlier work in monkeys and shows that rats can be used to study flexible decision-making too. Overall, it helps us understand the different ways the brain can solve the same problem.

## 2 Study Overview

The study by Pagan et al. looked at how rats can make decisions based on different contexts. The goal was to figure out how their brains change strategies depending on what kind of information is important at the time. While earlier research with primates showed that context changes how the brain works, it wasn't clear if the same thing happens in other animals like rats—or how different individuals might do things in different ways.

To explore this, the researchers created a task where rats listened to a series of sound pulses. Sometimes the rats had to decide which speaker (left or right) had more pulses. Other times, they had to decide whether the pitch of the sound was high or low. Before each trial, a context cue told the rats which rule to follow. This meant they had to change their decision-making strategy depending on the situation.

### 2.1 Training the Rats

The researchers used an automated training system that let rats perform the task in their home cages. Each rat completed over 120,000 trials, giving the scientists a lot of data. Because

the system ran automatically, it made sure all the rats were trained in the same way. This helped avoid training differences that could affect the results.

The sounds were presented in random order, and the context switched frequently. So the rats had to stay alert and be ready to change their strategy on each trial. This made the task a good test of cognitive flexibility.

## 2.2 How Well Did the Rats Do?

The rats learned the task really well and got high scores in both the location and pitch contexts. Psychometric curves—graphs that show how likely the rats were to make a certain choice depending on the evidence—showed that they were good at using the information.

Even though all the rats did well, they didn't all use the same strategy. Some rats paid more attention to the first few pulses, while others focused more on the later ones. This suggested that even when the behavior looks similar, the way the brain gets there can be different.

## 2.3 Why This Study Matters

This study wanted to find out if the same behavior could come from different ways of processing information inside the brain. To do that, the scientists not only looked at the rats' choices but also recorded brain activity and trained computer models (RNNs) to do the same task. This mix of behavior, brain data, and modeling gave a fuller picture of what was going on.

They used ideas from previous research, like the line attractor and selection vector, to build a model that could explain how context affects decision-making. Then they compared that model to what they saw in real rats and in artificial networks.

## 2.4 Pulling It All Together

One of the best parts of the study was how it combined three types of information: how rats behaved, how their neurons fired, and how artificial networks solved the same task. By looking at all three, the researchers showed that differences in brain activity matched up with different decision strategies.

They also broke down these strategies into three components: DIM, IIM, and SVM. Some rats relied more on one, others on a different one—but all of them succeeded. This means there isn't just one right way to make flexible decisions. The brain has options.

# 3 Theoretical Framework: Line Attractor Dynamics

## 3.1 What Is a Line Attractor?

One of the main ideas in this study is the concept of a "line attractor." Think of it like a path that brain activity follows when it's collecting information. As the brain receives more input, like sounds or other clues, its activity moves further along this line. Once the activity gets to a certain point, the brain can use that to make a decision. If no new input comes in, the brain just stays where it is on the line—it doesn't reset or drift randomly.

In this study, the rats were hearing pulses of sound. Each pulse added a bit more to the brain's current position on the line attractor. The more the brain heard, the further it moved along the line, getting closer to a decision. This system lets the brain remember and build on what it has already heard.

## 3.2 The Math Behind It

The math in the background helps explain how this all works. The brain's activity is written as a vector  $\vec{r}$ , which changes over time using a rule like this:  $\frac{d\vec{r}}{dt} = M\vec{r}$ . Here,  $M$  is a matrix that shows how neurons are connected and influence each other. If one direction (called an eigenvector) doesn't decay or grow—it just stays the same—that's the line attractor. The brain can move freely along that direction. All other directions fade away, so the system stays focused on the main path.

This setup makes it easy for the brain to keep track of what's important and ignore distractions.

### 3.3 What Is the Selection Vector?

The selection vector  $\vec{s}$  helps the brain know what kind of input matters. In the rat task, sometimes location was important, and sometimes pitch was. The input  $\vec{i}$  (like a sound pulse) projects onto  $\vec{s}$  to tell the brain how much that pulse should affect the decision.

The dot product  $\vec{s} \cdot \vec{i}$  shows how much of the input pushes the brain along the decision line. If the input matches the selection vector, it has a big effect. If it doesn't match, it doesn't do much. This lets the brain stay focused on what's relevant for each context.

### 3.4 Why This Is Believable in Real Brains

The idea of a line attractor isn't just a theory. Other studies have used it to explain how the brain handles memory, movement, and tracking space. In this study, brain recordings from the frontal orienting fields (FOF) in rats showed patterns that looked just like a line attractor: smooth changes during decision-making, stability when nothing new happened, and different paths depending on the context.

The fact that the real brain data matches the model so well makes it more likely that brains actually use something like this system in everyday thinking.

### 3.5 Why It Matters

This idea helps tie everything together. It explains how the brain can add up information over time, decide what matters, and stay stable until it makes a choice. It also helps explain why different rats (or people) might use different strategies but still end up making good decisions.

Even better, the same system can be used in artificial neural networks (like RNNs), so we can test and learn more using computers. That's why this framework is so useful—it helps us understand brains, build smarter machines, and learn how different minds can solve the same problems in different ways.

## 4 Comparative Study: Monkeys and Rats

### 4.1 What the Monkey Study Found

Before this study in rats, researchers like Mante et al. (2013) studied similar decision-making in monkeys. Monkeys were asked to focus either on the direction of motion or the color of dots on a screen, depending on a cue. The cue told them which kind of information to pay attention to for that trial.

Even though both color and motion were present, the monkeys had to pick out only the relevant part. Scientists recorded activity from the monkeys' prefrontal cortex (PFC), a brain area involved in planning and decision-making. They found that all the information—both relevant and irrelevant—entered the brain. But the PFC used context to decide which part of the input actually influenced the final decision.

They used a line attractor model to explain how this worked. Basically, only the inputs that matched the context moved the brain's activity along the decision path. This showed how flexible the brain can be when it comes to choosing what matters.

### 4.2 How the Rat Study Compared

Pagan et al. wanted to see if something similar happened in rats. Instead of looking at color and motion, they used sounds. Rats had to decide either where the sound came from (left or right) or what pitch it had (high or low), based on a context signal.

Just like in the monkey study, all types of sounds reached the rat's brain, but only the context-relevant sounds changed the final decision. The researchers recorded from the rats' frontal orienting fields (FOF), which plays a role similar to the PFC in monkeys.

They saw similar activity patterns: both relevant and irrelevant inputs came in, but internal processes in the brain picked the right ones to use. Also like in the monkeys, the rats' brain activity moved along a decision path depending on context—supporting the idea of a line attractor in rats too.

### 4.3 Why This Cross-Species Comparison Matters

These results suggest that both rats and monkeys solve decision-making tasks in a similar way—even though their brains are different. This tells us that certain strategies, like using a line attractor and selection vector, might be common in many animals, not just humans or primates.

This is important because rats are easier and cheaper to study than monkeys. If they use similar brain strategies, we can learn a lot about complex thinking without always needing primate experiments.

Also, this comparison shows that different animals might solve the same task in slightly different ways. Some rats responded to early sounds more, while others paid more attention to later ones—just like monkeys also showed variation between individuals. This variability is not a problem—it’s actually a clue about how flexible and adaptable brains really are.

## 5 Core Mechanisms of Contextual Computation

### 5.1 The Three Main Mechanisms

This study showed that the brain can use three main tools to adjust its decision-making based on context. These are:

- **Direct Input Modulation (DIM)**
- **Indirect Input Modulation (IIM)**
- **Selection Vector Modulation (SVM)**

Each of these helps the brain change how it reacts to the same input, depending on what’s important at the time.

### 5.2 Direct Input Modulation (DIM)

With DIM, the brain changes how strongly the input itself affects the decision. If something is important in the current context, the input has a big impact. If it’s not, the impact is small. This happens quickly, right when the input enters the system.

In rats that used more DIM, brain activity changed right away when a pulse came in. These rats also paid more attention to early pulses when making their decisions.

### 5.3 Indirect Input Modulation (IIM)

IIM is slower. Instead of changing the input directly, the brain lets the input go in normally but changes how it’s processed inside the network. This means that context effects show up only after the network has had time to work on the input.

Rats that used more IIM showed slower changes in brain activity after each pulse and were more influenced by later parts of the stimulus.

### 5.4 Selection Vector Modulation (SVM)

SVM is about changing how the brain “reads” the input. It doesn’t change the input or its path—it changes the internal settings that decide what the input means. This is like changing the lens through which the brain looks at everything.

SVM is also a slow mechanism. It works by updating the internal network settings based on the context. Rats that used more SVM had brain activity that took time to reflect the context, but still made good decisions.

### 5.5 How These Mechanisms Work Together

The study found that rats didn’t just use one mechanism. Instead, they used different mixes of DIM, IIM, and SVM. Some relied more on one, while others balanced all three.

To show this, the authors used a triangle diagram, with each corner representing one pure mechanism. All the rats fell somewhere inside the triangle, showing that they used combinations of strategies. The same was true for artificial neural networks.

## 5.6 Real Brain Evidence

The researchers saw all three types of modulation in the rats' brain data. Fast changes pointed to DIM. Slower, delayed responses pointed to IIM and SVM. They also looked at how rats made decisions and found that early or late decision weighting matched the kind of neural modulation seen.

They trained artificial neural networks to do the same task. These networks mostly ended up using SVM. Then the researchers created networks by hand to try out different combinations and showed that all of them could solve the task.

This proves that there isn't just one way to succeed. The brain has options—and different brains might choose different paths.

## 6 Neural Results and Variability

### 6.1 Different Brain Strategies for the Same Task

One of the most interesting things from the study is that all the rats were good at solving the task, but their brains worked in different ways. This means that even if the behavior looks the same, the brain can take different routes to get there. This kind of variation is not a problem—it's part of how flexible the brain is.

### 6.2 What Happened in the Frontal Orienting Fields (FOF)

The researchers recorded brain activity from the FOF, a part of the rat brain that helps with decisions and movement. It's like the rat version of the frontal eye fields (FEF) in monkeys.

They looked at how groups of neurons worked together while rats were making decisions. They saw patterns in the data that followed a common "decision path"—just like the line attractor model predicts. The brain activity changed in a smooth way as rats gathered information and moved closer to a choice. These changes lined up with the sounds the rats were hearing and the decisions they made.

### 6.3 Measuring How Fast the Brain Responds to Context

To understand how the brain reacted to context, the scientists came up with a score called the "slope index." This score measured how quickly the brain's activity changed when it heard a pulse that was relevant or irrelevant to the current context.

Some rats had big, fast changes right after a pulse—that meant they were using DIM, where context changes the input early. Other rats had slower changes, showing that they were using IIM or SVM, where the context matters more during or after processing.

This slope index showed that there isn't just one kind of brain strategy. Instead, each rat had its own style, somewhere on a spectrum from fast to slow response.

### 6.4 Linking Brain Activity to Behavior

The team also looked at how the brain activity matched what the rats did. They used a method called the behavioral kernel, which shows how much influence each sound pulse had on the rat's decision.

The results were clear: rats with fast neural responses (high slope index) paid more attention to early pulses. Rats with slow responses (low slope index) gave more weight to later pulses. This match between brain activity and behavior proved that different brain styles lead to different ways of solving the same task.

### 6.5 Why This Matters

These results show that the brain doesn't need to use the same method every time. Different animals—and maybe even different people—can succeed in the same task using different brain strategies. That's a big deal for science, because it means we shouldn't always expect to find one "right" answer about how the brain works.

This also helps explain why personalized brain models or treatments might be more effective than one-size-fits-all approaches. Everyone's brain might be wired a little differently, but still capable of solving the same problems in its own way.

So overall, this part of the study shows how much we can learn from looking at brain differences—not just similarities—and why that variability is something to pay attention to.

## 7 Artificial Neural Models

### 7.1 Training RNNs to Imitate Rats

The researchers also used artificial neural networks, specifically recurrent neural networks (RNNs), to try and mimic how the rats solved the task. These networks were trained to do the same job as the rats—listen to a series of pulses and make a decision based on context.

They used a training method called backpropagation-through-time (BPTT), which helps the network learn by adjusting connections after each mistake. Over time, these networks learned to perform the task very well. Surprisingly, the way the networks processed the information looked a lot like how the rats' brains did it.

### 7.2 What the Networks Did

Most of the trained RNNs ended up using strategies that depended heavily on adjusting internal rules, similar to the SVM strategy in rats. That means instead of changing the input, they changed how the input was interpreted inside the network. This mirrors what was seen in some of the actual animals.

The networks followed low-dimensional paths that resembled the line attractor model used to explain the rat brain. This showed that RNNs can naturally develop brain-like strategies—even when trained only on behavior.

### 7.3 Building Special RNNs by Hand

To learn even more, the researchers didn't just train networks—they also created them from scratch. They adjusted the inner settings of the RNNs so each one would use a different mix of DIM, IIM, and SVM strategies. This let them test exactly how each type of strategy worked.

They mapped these networks onto a triangle diagram, where each corner represented one strategy. Networks closer to a corner used mostly that strategy, while others used a blend. This method gave them a complete picture of all the ways a network could solve the task.

### 7.4 Why These Models Matter

These artificial networks didn't just copy the rats—they gave new insights into how different strategies work. The models helped explain why some strategies lead to fast reactions (like DIM) and others rely more on slower processing (like SVM or IIM).

Also, the researchers matched specific networks to specific rats based on their behavior and brain activity. This showed that the same patterns could happen in both natural and artificial systems.

### 7.5 Big Picture Takeaway

Using RNNs helped the scientists test their ideas and see how different brain strategies can work in practice. These networks are useful not just for copying brain behavior but also for helping us understand how that behavior happens.

This part of the study proves that computers can do more than imitate—they can be tools for learning how the brain solves complex problems in different ways.

## 8 Conclusion

This study, titled "Individual variability of neural computations underlying flexible decisions" by Pagan et al., is a major step forward in understanding how the brain can solve the same problem in different ways. It combines biology, math, and computer models to show that flexibility in decision-making comes from more than just one pathway or strategy.

The most important idea in the paper is that there are three different ways the brain can adjust to different contexts: Direct Input Modulation (DIM), Indirect Input Modulation (IIM), and Selection Vector Modulation (SVM). These three tools give the brain different ways to pick

out what's important in a task and ignore what's not. And the amazing part is that different rats used different mixes of these tools, but all of them still did really well.

Here's what makes this study special:

- The task was very carefully designed with sounds (pulses) that could be grouped by either location or pitch.
- Each rat did over 120,000 trials, which gave a lot of data to work with.
- Brain activity and behavior were recorded at the same time.
- They broke down the task into a triangle of strategies (DIM, IIM, SVM).
- They even built computer networks (RNNs) by hand to test every possible strategy mix.

One of the coolest things they found was a strong link between how fast the brain reacts (neural slope) and how early the animal makes a decision (behavioral kernel). Fast brain responses meant the animal made quicker decisions based on early sounds.

## 8.1

Who Would Be Interested in This Paper? This study is useful for a lot of different people:

- Neuroscientists who study how the brain makes choices.
- Computer scientists who build smart machines based on the brain.
- Doctors and researchers looking into why people think or decide in different ways.
- Engineers designing personal brain-computer interfaces.

It could also help teachers, therapists, or even software developers who want to understand how different people process information.

## 8.2

Ideas for Future Research The paper opens up some exciting future directions:

- What if the decision axis isn't always the same in both contexts? That would turn the triangle into a 3D shape and change everything.
- Could this task be used with humans or monkeys to see if they also use the same strategies?
- Better recording tools could help see exactly when and where the brain uses each type of modulation.
- Can we get better at measuring the selection vector  $\vec{s}$ ? That would make the theory even stronger.

## 8.3

How Has It Been Used So Far? Since it came out online in late 2024 and in print in March 2025, this paper has already been used in several new studies. Some of the areas it has influenced include:

- Research on how people make decisions and why they differ.
- Training methods for advanced neural networks in AI.
- New models for how the brain handles changing tasks.
- Comparisons between different species' decision strategies.

It's also being used in debates about whether the brain blocks out distractions early on or just figures out what's useful later.

**In short**, this paper gives us a smarter way to think about flexible decision-making. It shows that brains—and machines—can reach the same goal using different paths. That's a powerful idea with lots of applications in science, medicine, and technology.