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Understanding the Role of Anxiety and Behavior in Learning through Zebrafish: A Computational Model

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Abstract

Amidst a post-pandemic world, understanding the mechanisms of associative learning and anxiety can offer crucial insights into the fundamental processes underlying the human mind, paving the way in a globe where mental health issues have surged globally. This paper explored how anxiety affects associative conditioning and behavior, introducing a computational model simulating zebrafish behavior. The research aimed to address how zebrafish respond to visual and auditory stimuli by associating cues with rewards or punishments, providing insights into learning processes. Through tracking movement and a modeled anxiety level influencing decision-making, the simulation revealed patterns in zebrafish behavior, highlighting the roles of anxiety and cues in associative learning. The findings underscored key insights into the neural mechanisms underlying learning and attention, while also identifying potential applications for understanding anxiety disorders and survival strategies within our own species. Ultimately, this research provided a framework for applying similar models to other animals and humans, rendering it an invaluable asset across diverse scenarios.

Keywords: Associative conditioning, Attention, Neural circuits, Zebrafish, Computational model, Learning and memory, Optogenetics, Classical conditioning

1. Introduction

By stimulating results within more manageable neural processes that remain similar to those of complex ones in higher vertebrates and even humans, this research hopes to uncover the fundamental principles that lie behind learning processes.

The applications of understanding these processes are boundless. Understanding brain development would help uncover more about the function of our basic neural circuits and can aid in treating disorders like Alzheimer's disease and dementia (Solomon et al., 2014). Comprehension of basic animal desires and adaptations can also serve to show how organisms learn and adapt to their environments, showing more about how memory plays a real role in the real world, and possibly leading to strategies for managing anxiety and fear for enhancing learning and memory in both humans and animals (Adams & Kafaligonul, 2018). Anxiety is a normal response controlled by the amygdala, which prepares us for fight-or-flight and helps detect threats (Nemeroff & Craighead, 2024). However, prolonged or intense anxiety can lead to issues like PTSD, panic disorders, and OCD. These conditions are often under-researched and underfunded compared to other mental health problems. Regarding this issue, the simulation hopes to pave the way in providing fundamental knowledge in models used for more complex structures and allows for comparisons across real-life and separate simulations to identify common patterns and unique adaptations (Burgess & Huber, 2008). The use of stimulating anxiety-inducing stimulus hopes to help identify specific neural pathways or molecules involved in anxiety responses, which could lead to the development of targeted therapies that modulate these pathways to alleviate anxiety symptoms.

Research on associative conditioning began a hundred years ago when a theory was established that states behavior can be modified or learned based on a stimulus and a response (Ferrari et al., 2012). The fundamental principles of associative conditioning, where organisms learn to associate stimuli with specific outcomes, such as rewards or punishments (Pavlov & Anrep, 1927; Wagner & Rescorla, 1972) involve synaptic plasticity mechanisms, such as long-term potentiation (LTP) and long-term depression (LTD), which strengthen or weaken connections between neurons based on experience (Bliss & Collingridge, 1993). Attention, which is a core component of neural function and adaptation, modulates these learning processes by directing neural resources toward salient stimuli while suppressing responses to irrelevant ones (Desimone & Duncan, 1995).

Neuroimaging studies have identified brain regions involved in attentional control, including the prefrontal cortex, parietal cortex, and superior colliculus (Corbetta & Schulman, 2002). Despite the last century of progress, some gaps remain in understanding the interactions between attentional mechanisms and associative learning at the neural circuit level. Recent advancements have provided tools that make it much easier to manipulate and observe neural activity with high precision (Deisseroth, 2011; Markram, et al., 2015).

In the field of behavioral conducting experiments, foundational studies originating in the 19th century have evolved into more contemporary techniques used today (Best & Paquet, 2008). In the beginning, Ivan Pavlov, a Russian physiologist, realized that dogs could be conditioned to associate a stimulus, such as a bell, with the presentation of food. After training, a dog would begin to salivate at the sound of the bell, even when there is no food present (Pavlov & Anrep, 1927). Building on this work, a researcher named Edward Thorndike explored reinforcement behavior, which led to his “law of effect” which proposed that behaviors followed by positive consequences are more likely to be repeated (Thorndike, 2000).

While Pavlov’s work in stimulus training led to a whole culture of dog obedience drilling, it also led to many modern techniques and applications in neuroscience which has led to the exploration of neural mechanisms underlying conditioning today (Mazzucato, 2022). To align with the evolution of experimental techniques and advancements in neuroscience research, zebrafish (Danio rerio) have offered unique advantages as a model organism for studying behavior and cognition (Burgess & Huber, 2008). It is very easy for neural development to be studied, as zebrafish have transparent embryos that allow researchers to study early brain circuitry and developmentally regulated behaviors. Zebrafish also exhibit complex behaviors, such as anxiety, that are very easily used in translational research for medicine and studying in other species. The comparative studies from zebrafish, as they share genetic and physiological similarities with higher vertebrates, including humans, make findings from them valuable to bridge the gap between basic research and clinical applications in neuroscience.

2. Computational Model

Similarly to many contemporary experiments involving behavioral conditioning and attention, this study utilizes zebrafish (Danio rerio) with classical conditioning paradigms to learn to associate auditory cues with either rewarding or aversive stimuli (Colwill & Creton, 2005). The simulation begins with two sides on either end or places a single zebrafish which moves at random through a virtual environment for the first 10 iterations. It encounters visual stimuli that the simulation associates with different sounds, modeling the sound of a predator and the sound of a bell, to simulate association. The zebrafish's movements and outcomes are tracked, in counters for deaths and food encounters. Anxiety levels and modeling of attention span fluctuate based on environmental cues, influencing the zebrafish's behavior. More details on the simulation are explained in Section 3.

Simulations, like the computational model in this study, offer controlled, repeatable environments for testing hypotheses ethically and cost-effectively without involving animals or humans, but they cannot fully replicate the complexity of real-world biological systems, requiring validation against real-life experiments (Vashishat et al., 2024).

Based on this simulation framework and established principles in neuroscience, we proposed the following predictions. Firstly, for the role of attention span, it is likely that zebrafish modeling longer attention spans will demonstrate enhanced proficiency in associating conditioned stimuli with specific outcomes. Attention span is defined as the duration and quality of focus an organism can maintain on a specific stimulus or task. In zebrafish, as in other

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vertebrates, attention plays a crucial role in learning by directing sensory processing toward relevant stimuli and filtering out distractions. Thus, it is expected that zebrafish with longer attention spans would allocate more of their cognitive resources to processing auditory cues and associating them with different outcomes (Adams & Kafaligonul, 2018). This would enhance the probability of specific responses, such as approaching food or avoiding predators.

Secondly, on the opposite end of the spectrum, a short attention span would likely lead to longer behavioral responses and the animal would never learn (Best & Paquet, 2008). A short attention span makes it likely that the fish would be more susceptible to environmental distractions, which can be modeled through the addition of extra visual cues as distractors, which interferes with learning and makes it less likely to associate cues with actions (Burgess & Huber, 2008). If the attention span is long enough to associate the unconditioned stimulus with the conditioned stimulus, the animal can learn. But if it cannot, in the case of the real world, failing to associate a sound with danger can result in much lower survival chances for an animal (Mazzucato, 2022).

The hypothesis of this paper relies on two factors: the ability of the zebrafish to retain and recall learned associations between auditory cues and specific outcomes over time, or memory, and how the level of motivation or drive towards achieving a goal influences the zebrafish's engagement with learning tasks and the reinforcement value of outcomes. It is assumed that when met with a particular goal, motivation that is maintained going upwards during learning, which is involved with attention, is translated into motion which is characterized by purposeful and goal-directed behaviors aimed at achieving the desired outcome associated with the goal. This hypothesis suggests that the alignment of motivational states and attentional focus optimizes the zebrafish's ability to learn and adapt its behavior in response to environmental stimuli. By investigating the interactions between action and motivational/attentional processes, this research hopes to understand how decision-making, and anxiety play a role across comparative studies in different species.

2.1 Diagram

Before developing the simulation, a simplistic diagram was made to model what it would look like. There were three separate iterations of the simulation planned, and this model was meant to represent the core functions of the simulation that were necessary to properly create a realistic representation of the zebrafish's learning and adaptation processes.

The original goal was to create a visual representation that simplifies the complex interactions involved in associative conditioning and attention mechanisms in zebrafish. The diagram was intended to distill the experiment into its most essential components: the environment, stimuli, and outcomes.

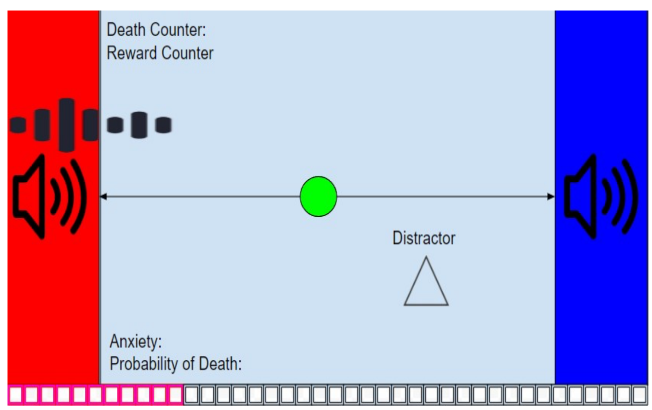

Figure 1. Flowchart of Zebrafish Simulation Design. A schematic representation of the initial simulation framework, showing the zebrafish's movement across an environment with auditory cues linked to positive (food) and negative (predator) stimuli. The diagram highlights the role of random initial movements and the incorporation of anxiety and distractor elements in later iterations.

Illustrated by Figure 1, by having the zebrafish begin in the middle and move either left or right, the diagram captures the essence of decision-making in response to environmental cues. On either side, a sound would play which distinguishes between positive(food) and negative(predator) outcomes. Associating these specific auditory cues with each rectangle highlights the role of sensory stimuli in associative learning.

The counters or indicators next to each rectangle provided a straightforward way of tracking the zebrafish's interactions in the environment over time. The way the program was intended to work was to take the first 10 iterations as a randomizer (basically ensuring that each simulation would be different to model the uniqueness of each zebrafish), where the zebrafish would move randomly (as if it has just been born and does not have the knowledge to associate anything with anything else yet). After each iteration, the system would add to the zebrafish's anxiety levels and its

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association of bad sounds with bad outcomes, and good sounds with good outcomes, which would determine the zebrafish's pathfinding after the first 10 random iterations. A distractor was also planned, which would introduce a new sound and new location into the system after a certain number of iterations (50-70) and would model unfamiliar occurrences in the zebrafish's life.

2.2a First Simulation – basic

In Figure 2, the first simulation represents a fundamental model designed to study associative conditioning in zebrafish by simplifying their interaction with stimuli and outcomes. This initial step involves a straightforward setup where zebrafish can move towards two distinct sides of a virtual environment, each associated with a specific consequence. This model does not incorporate anxiety, attention span, or the probability of death, as the purpose of this simulation is to serve as a comparison for later more complex simulations and to offer results on what would happen to a zebrafish that did not have anxiety or much attention.

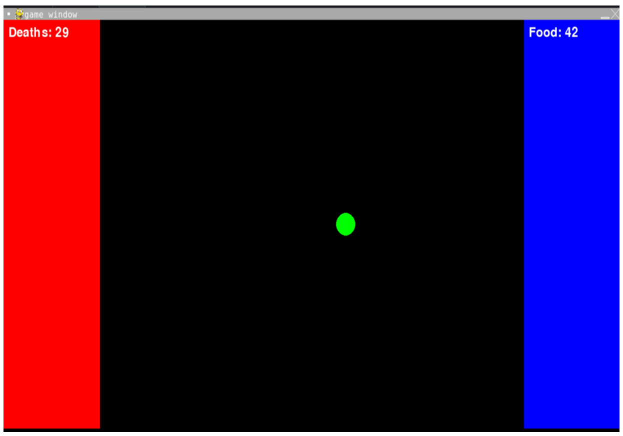

Figure 2: Basic Simulation Probability Framework. A visual representation of the first simulation iteration, where zebrafish movement is based purely on associative learning without anxiety or complex decision-making mechanisms. This figure illustrates the environment setup and the basic probability-driven interactions between zebrafish and stimuli.

This zebrafish still runs on the first ten iterations determining how it associates noises with a positive or negative outcome. The first 10 iterations of random movement were implemented to simulate the exploratory behavior observed in newly born zebrafish, which lack prior associations with their environment. This randomness ensures diverse outcomes and creates a realistic starting point for learning processes. However, this fish does not adjust for anxiety and does not adjust for its awareness of threats in its environment, and only learns to follow the same patterns of success or death. Often, it will go towards the outcome that it is most familiar with because it learns to keep repeating the same patterns that it has already experienced. This is discussed further in the results section.

2.2b Probability

As shown in Figure 3, the zebrafish's modeled probability is stored as 1s and 0s which represent the positive and negative outcomes. As the zebrafish experiences either a predator's sound or receives a negative outcome, or the sound of a bell which it associates with food, the system adds that information into a list that represents the zebrafish's memory. Later, this memory will also be altered by anxiety, but in this simulation, the memory controls the likelihood of the fish moving towards food or its death. It is important to also realize that the system automatically stops itself if the fish moves towards the death side too many times in a row, which represents the fish being eaten.

```
[0, 1, 0, 1, 0, 0, 1, 1, 1, 0, 1, 1, 0, 1, 0, 1, 1, 0, 0, 1, 0, 0, 0, 0, 1, 1, 0, 1,
0, 1, 1, 0, 0, 1, 1, 1, 1, 1, 1, 1, 0, 1, 0, 1, 1, 0, 1, 1, 1, 1, 0, 1, 0, 0, 0, 1, 1
, 1, 1, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 0, 0, 1]
84
[0, 1, 0, 1, 0, 0, 1, 1, 1, 0, 1, 1, 0, 1, 0, 1, 1, 0, 0, 1, 0, 0, 0, 0, 1, 1, 0, 1,
0, 1, 1, 0, 0, 1, 1, 1, 1, 1, 1, 1, 0, 1, 0, 1, 1, 0, 1, 1, 1, 1, 0, 1, 0, 0, 0, 1, 1
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```

Figure 3: Probability Storage Mechanism in the Basic Simulation. A depiction of the memory system storing positive (1) and negative (0) outcomes for zebrafish behavior. The figure shows how these probabilities influence future movement decisions, with mechanisms halting simulations upon repeated "death" scenarios.

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2.3 Anxiety and Death Probability Simulation

The way anxiety was implemented was by first determining how seeing a predator in the wild and receiving a reward with a visual stimulus works. Zebrafish, like many animals, have developed the ability to detect and respond to visual cues in their environment (Ferrari, et al., 2012). When a zebrafish sees a predator (represented by a negative visual stimulus, like the red rectangle), its sensory systems immediately register the potential threat. Once this visual stimulus is perceived, it is processed by the brain and sent to the optic tectum, which plays a significant role in processing visual information and initiating appropriate responses. The brain then assesses the visual input and determines the level of threat or reward associated with the stimulus. Every time that the brain concludes this stimulus to be a threat, it triggers an escape response that heightens anxiety which makes it more likely for a fish to escape from danger (Rui, 2013).

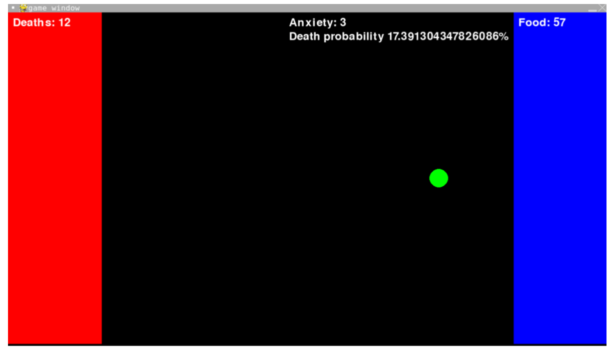

Figure 4: Anxiety and Death Probability Simulation Dynamics. A graphical overview of anxiety integration in the simulation, showing how anxiety levels fluctuate based on encounters with predator zones and their impact on zebrafish decision-making. The figure illustrates the interaction between anxiety thresholds, survival rates, and adaptive behaviors.

As shown in Figure 4, in the simulation, this was modeled through an “anxiety level” variable which increases whenever the zebrafish encounters the threat zone. The incremental increase in anxiety based on consecutive encounters with threats reflects real-world patterns where repeated exposure to danger amplifies stress responses (Rui, 2013). This design choice was informed by studies showing that the magnitude of anxiety responses scales with the frequency and intensity of perceived threats. However, the increase in anxiety level is not fixed; it varies depending on the number of consecutive encounters with the threat zone and how close the zebrafish is to “death” (a high number of encounters with the red rectangle). The anxiety level increases by a variable amount (1 to 20 levels), and increases by a higher amount when the zebrafish is close to death or becomes much more significant if the zebrafish hits the threat zone multiple times in a row, which reflects a heightened sense of danger. As anxiety increases, the zebrafish becomes more and more uncertain about its choices until it reaches a certain threshold, which starts at twenty levels and changes based on how close the zebrafish is to death. After this threshold, the zebrafish becomes significantly more likely to hit the positive zone in certain (case analysis in the results section) cases, and every time it hits the reward, anxiety decreases by ten.

The anxiety threshold was set to 20 to reflect moderate anxiety levels observed in prior behavioral studies (Marks, 1987), where heightened vigilance can promote survival without leading to detrimental stress responses. This threshold serves as a balance point to simulate realistic decision-making influenced by anxiety without creating exaggerated effects that could skew the outcomes.

Additionally, anxiety decreases by one every time the zebrafish goes into the reward section when anxiety levels are already low. The threshold for anxiety also goes down as the zebrafish’s lifespan continues. To simulate movement better for the experiment, a function was also added so that when there is high anxiety, the zebrafish take a lot longer to make their decisions(paranoia), and rather than picking one choice directly and traveling towards there, it decides for every moment that it moves whether it wants to keep moving in that direction or swim somewhere else. Small factors like this help to make the simulation more realistic and representative of real-world settings.

Anxiety levels within the simulation are classified into three ranges: low (0–10), moderate (11–20), and high (21 and above). These thresholds were determined based on behavioral studies suggesting that moderate anxiety levels promote adaptive behaviors, while excessively high levels impair decision-making (Marks, 1987; Rui, 2013). Anxiety levels increase incrementally with repeated encounters with threats, and decrease after positive reinforcement (e.g., moving toward the reward zone). This classification helps simulate a realistic gradient of stress responses in zebrafish behavior.

High anxiety levels in the simulation influence zebrafish behavior in a dual manner: while moderate anxiety

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encourages risk-averse behaviors, excessive anxiety can impair decision-making and lead to maladaptive patterns. When anxiety levels approach or exceed the threshold (e.g., above 20), zebrafish may exhibit hypervigilance, making decisions more frequently based on immediate threats or rewards. This heightened state can drive zebrafish to seek positive stimuli, such as food, as a form of relief. However, if the anxiety remains unchecked or increases uncontrollably, it can lead to erratic or overly cautious behaviors that prevent effective threat avoidance. For example, zebrafish with high anxiety may hesitate near the threat zone, increasing their risk of death due to prolonged exposure to danger. This explains the apparent contradiction: high anxiety can momentarily guide zebrafish toward positive outcomes, but when extreme, it disrupts balanced decision-making, ultimately raising mortality rates.

By incorporating this anxiety mechanism, the simulation mimics real-world learning and behavioral adaptation in zebrafish. Understanding this anxiety function that is meant to keep organisms away from threats is especially important, as help for anxiety disorders in the real world is very underdeveloped, and by looking at these organisms, it would be possible to connect these behaviors to human issues (Nemeroff & Craighead, 2024).

Figure 5 shows a short excerpt of the code for the simulation, which covers some of the code for anxiety, and was made in an open-source, cross-platform library run with Python. This part of the simulation tracks encounters with the two zones and introduces the randomness of the first ten iterations to influence the last ninety iterations. Anxiety is used to fluctuate based on encounters. This excerpt of code depicts how anxiety changes with each movement, as shown with the counter and the value of runs.

```
if current_x - 20 <= 200:
    counter.append(0)
    deaths += 1
    anxiety += random.randint(1, 10)
    runs += 1

    current_x = initial_x
    if runs < 10:
        move_direction = random.choice([-move_speed, move_speed])
    else:
        temp = random.randint(0, len(counter) - 1)
        if counter[temp] == 0:
            move_direction = -5
        elif counter[temp] == 1:
            move_direction = 5

elif current_x + 20 >= 1080:
    counter.append(1)
    food += 1
    if (anxiety >= 20):
        anxiety -= 10
        food += 1
        counter.append(1)
    else:
        anxiety -= 1
    runs += 1

    current_x = initial_x
    if runs < 10:
        move_direction = random.choice([-move_speed, move_speed])
    else:
        temp = random.randint(0, len(counter) - 1)
        if counter[temp] == 0:
            move_direction = -5
        elif counter[temp] == 1:
            move_direction = 5
```

Figure 5: Anxiety Function Code Excerpt. A code snippet highlighting the implementation of anxiety dynamics in the simulation. This excerpt demonstrates how anxiety levels change with each movement, with variables accounting for threat encounters, rewards, and the progression of anxiety thresholds.

2.4 Introduction of a Distractor

In the real world, animals often encounter unfamiliar distractions that impact their learning and adaptation behaviors. By simulating this distractor in the simulation, it adds enhanced realism to how an organism would develop in the wild.

Distractors were designed to become randomly between iterations 50 and 70 to mimic real-world unpredictability in an organism's environment. This range was selected to allow sufficient time for the zebrafish to establish baseline behaviors before encountering additional stimuli, enabling an evaluation of how distractions influence already-formed associations.

The inclusion of the distractor is to allow for the study of how the zebrafish's attention is allocated, and how it is maintained. By putting an unfamiliar sound into the environment, it is possible to examine how the zebrafish prioritizes certain stimuli, perhaps unfamiliar vs. familiar, and to see how distractions influence the learning process of the zebrafish.

As shown in Figure 6, there is now a green triangle present on the screen in the bottom left. To make it so that the zebrafish has a response to the distractor, a separate "decision-making" function was implemented where depending on anxiety, the zebrafish is more likely to trust the distractor or not when presented with either going to

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the distractor or going to the death or food zone. Depending on the zebrafish's previous experiences, it might ignore the distractor completely, or choose it as an alternative to the other choices. If the zebrafish has a certain amount of trust, it might pick one or two choices rather than just one.

In the previous two simulations, the zebrafish could only move in two directions, but with the introduction of the distractor, it was necessary to provide fluid movement to the zebrafish, which made the simulation look more realistic.

There is also a new variable called focus, where the zebrafish learns to associate all unfamiliar sounds as unnecessary and focus only on the two choices that influence the zebrafish's life. This is done by updating a list every time a zebrafish interacts with a distractor, which simulates a random positive or negative effect on the zebrafish like a normal distractor in the world would. This simulates real-life stressors or threats, and thus also adds anxiety to the zebrafish. Anxiety, again, influences the zebrafish's decision-making, which influences how likely the zebrafish would interact with the distractor.

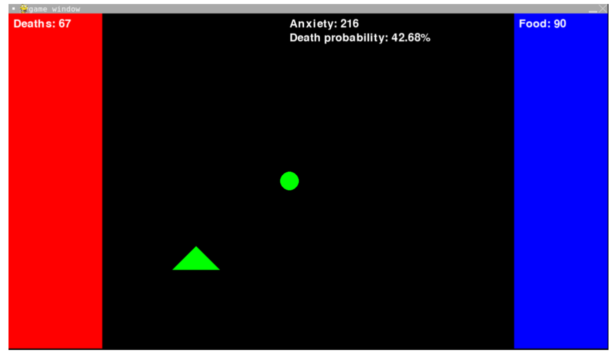

Figure 6: Impact of Distractors on Zebrafish Decision-Making. Description: A simulation screenshot showing the introduction of a distractor (green triangle) alongside food and predator zones. The figure illustrates the expanded decision-making model, where zebrafish navigate additional stimuli, impacting focus, anxiety, and survival.

```
distractor_reappear_time = random.randint(200, 1000)  # Random initial time
for distractor to reappear
distractor_timer = 0
distractor_anxiety_increase = 15  # Amount of anxiety increase when touching
the distractor
```

```
    # Update distractor timer and reappear logic
    if not distractor_active:
        distractor_x = random.randint(250, 1030)
        distractor_y = random.randint(50, 670)
        pygame.draw.polygon(screen, (128, 0, 128), [(distractor_x,
distractor_y), (distractor_x + distractor_width / 2, distractor_y +
distractor_height), (distractor_x - distractor_width / 2, distractor_y +
distractor_height)])
        distractor_active = True
```

Figure 7: Distractor Mechanism Code Excerpt. A code excerpt showcasing the implementation of distractor stimuli in the simulation. The snippet demonstrates the randomized appearance of distractors and their influence on zebrafish behavior, including updates to anxiety levels and decision-making algorithms.

In Figure 7, the provided code snippet shows parts of how the distractor is introduced at random intervals, simulating how random events happen in any organism's life. This distractor is meant to mimic real-world scenarios, where these unexpected stimuli would influence the behavior of the zebrafish or cause distractions from normal choices. These new factors, such as focus and decision-making, enhance realism and the new movement patterns and can contribute to a more nuanced understanding of animal behavior accurately.

2.5 Experiments

In addition to the three main versions of the simulation, additional experiments meant to simulate other aspects of behavior and anxiety were made, which were not significant enough to be included in the results section but are still interesting in looking at how the simulation was affected.

The first was by setting anxiety to a high at all times, which resulted in the zebrafish almost always heading purely towards the food side and ignoring all distractors. However, due to the way anxiety was programmed with still being based on past experiences, sometimes high anxiety resulted in a zebrafish constantly going towards death, which is convenient as this stimulates real-life anxiety disorders that can make someone choose the wrong decisions rather than helping them stay away from danger (Nemeroff & Craighead, 2024). The seldom use of the distractors also shows paranoia, which is a prevalent symptom of anxiety disorders.

The second experiment that returned interesting results was by making anxiety spike up randomly to a high. This often resulted in two scenarios: either the zebrafish would constantly have to relieve itself by choosing the food option

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to get rid of anxiety, or it would get stuck in a loop where anxiety would keep going higher and higher, due to the zebrafish getting exposed to the threat side but not leaving that area. This was interesting as it displayed compulsive behavior, where the zebrafish repeatedly sought the food area to alleviate itself, and highlighted how high anxiety could trap a zebrafish in a negative feedback cycle, showing how anxiety can sometimes cause individuals to get stuck in harmful patterns.

3. Results and Discussion

In this experiment, there were three different iterations of the simulation that made major changes that simulate the learning processes of a zebrafish. The first, being a simplistic original model, was used as a baseline and does not incorporate anxiety, focus, or many other mechanisms, and is more of a probability machine (2.2). The second incorporated fear, anxiety, and other small factors that model how the brain employs certain mechanisms in order to affect learning and behavior, which ultimately affected survivability in the wild for all creatures (2.3). The third, which added in distractors using focus and decision-making, created more unpredictability in the system, and finished off the program, creating a realistic simulation of how attentional processes work in the real world (2.4). Results from all three simulations have been recorded and will be examined as follows.

3.1 Simulation 1

In this experiment, a hundred simulations were run and tested for their % survived, the average number of times the fish went towards the positive and negative sides, the number of fish that died, and the average number of times the fish went towards the positive and negative sides in the first ten trials.

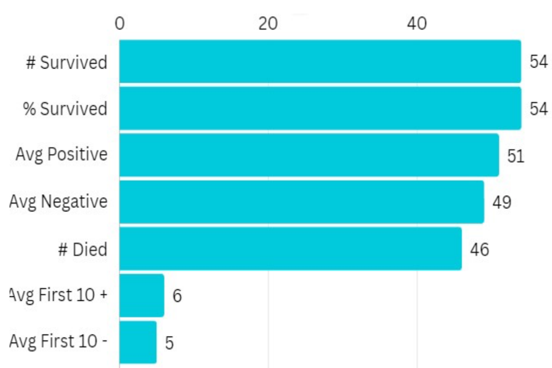

Figure 8. Figure of simulation 1

Looking at the simulation results, 54% of the fish survived. This percentage was expected, as it was based on the conditions modeled in the first iteration, which focused a lot on probabilities without additional factors such as anxiety and fear. This meant that the first ten outcomes were very important for determining the rest of the results, which was what happened, as shown by the ~50% divide between average positive and average negative for the first ten. Looking at this experiment, almost every single result was a 50% divide, which made sense, seeing as this is a scenario where a fish adapts based on its past behaviors. This first simulation was necessary, as it showed what behavior would be exhibited given no additional factors such as fear, anxiety, decision-making, (much) adaptation, or anything else, serving as a true baseline. However, it is important to note that although the statistical results of the experiment for Simulation 1 expectedly did not return anything significant, looking at individual trials was interesting, as a result of how the simulation was set up (2.2). The fish still had a decision-making module, simple as it may be, but it adapted based on what scenarios it was familiar with and how many times it has experienced death. Often, this resulted in being killed immediately, as the fish only experienced threats for its whole lifespan and thus did not know how to run away from threats, or the fish might never go towards threats at all. By changing the amount of "decision trials", the first few trials which were random to decide the rest of the experiment, which was set to 10 normally, this also changed the likelihood of different decisions throughout each experiment. This early phase showed an initial adaptation pattern which is crucial in understanding how organisms adjust their behaviors to optimize survival.

3.2 Simulation 2

Similarly to Simulation 1, a hundred simulations were run with the second iteration, but with two new measurements: Average anxiety, which was what the average anxiety was for every fish throughout the experiment,

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and the average % of death for each fish at the half-way point of each iteration for all hundred fish. It was important to place this average % of death at the halfway point, as placing at the beginning or the end would return inaccurate results since the % of death would either be 100% at the beginning or 0% / 100% again at the end. At the 50% mark, the fish has already well gone past the first 10 "decider" trials and has had time to adapt to anxiety and fear to make decisions, and thus would be a good place to measure % of death.

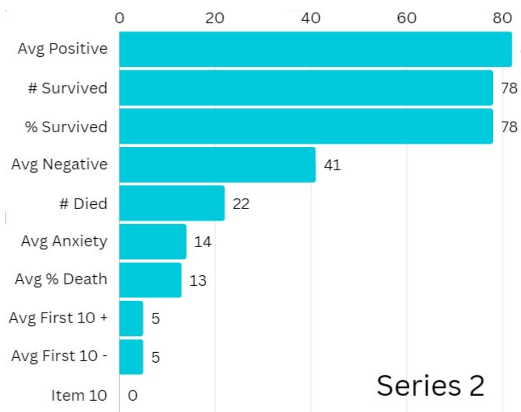

Figure 9. Figure of simulation 2

This simulation resulted in a much higher % of survival, with 78% of the fish surviving. This indicated an improvement in survivability, which indicated how the presence of anxiety and fear may have influenced behavior so that the zebrafish would take more cautious or risk-averse strategies. The most interesting part about the results of Simulation 2 was how average positive responses (Avg Positive) were significantly higher than average negative responses (Avg Negative) (82 vs. 41). Going into Simulation 2, the purpose was to see how anxiety affected behavior in response to perceived threats, and these higher positive responses indicate a large impact on anxiety when presented with anxiety-inducing stimuli. Again, the first ten trials were still a 50/50 split, which made sense as the first ten trials remained random for all simulation versions, to create diverse results between the experiments.

Looking at the new score, average anxiety score (Avg Anxiety), which returned 14, shows that anxiety was a notable factor affecting behavior. The anxiety threshold (see 2.3 for more detail) was set to 20 for this experiment, and due to how the anxiety mechanism works, the score shows that anxiety was balanced throughout the experiment, which correlates with the high positive score for the number of fish that survived. The few outliers, where fish were not able to balance anxiety, and thus ended with very high anxiety scores, mostly did not survive, and showed how when anxiety reach a certain point, it was more harmful to an organism than helpful. The average percentage of death (Avg % Death) at 13% helped to show how despite the high survival rate, a significant portion of the population still did not survive, highlighting where behavioral responses might need further study or adjustment. These simulation results showed how moderate levels of anxiety caused more vigilant behavior and could help both animals and humans avoid potential threats, which increased the chances of survival. This suggested that anxiety, within a certain range, was adaptive and beneficial. The 82 vs. 41 split of the positive vs. negative responses showed how anxiety prompted the zebrafish to make safer choices. This showed the role of anxiety in enhancing protective behaviors, and therapeutic interventions could be designed to harness this positive aspect of anxiety, helping individuals to channel their anxiety toward making safer, more informed decisions rather than succumbing to panic. However, the few outliers with higher anxiety did not survive, which showed how excessive anxiety was detrimental. Relating this to the outside experiment, where anxiety was set to a constant high (2.4), it showed how anxiety disorders were extremely dangerous to an organisms' health. This dual effect aligns with observed patterns in the data displayed in Section 2.3A: Anxiety and Death Probability Simulation. In the real world, anxiety disorders are majorly not studied or focused on in the scientific world, and the area requires better tools and strategies for managing high anxiety to prevent negative outcomes such as with the outliers.

3.3 Simulation 3

With the distractor simulation, no other metrics were added, but it is important to remember that there are two new functions: decision-making and focus. Here we will see how decision-making and focus, with the distractor, changed the results from Simulation 2, which had anxiety and fear.

The survival rate was slightly lower compared to the second iteration (78%), which showed that the introduction of distractors might have slightly decreased the survivability of the zebrafish. However, there was still a high average

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positive behavior score of 81, and an average negative score of 51, which showed that negative behaviors were likely prevalent but not dominant in the experiment. The anxiety score was higher, much closer to the threshold, showing that distractors made it more difficult for the fish to balance anxiety levels and they ended up being more elevated, which led to an increased likelihood of losing control and developing disorders (where anxiety gets too high and the zebrafish cannot control it). This correlated with the higher percentage of death (21%), showing that distractors made a difference in higher mortality rates. It is also important to note that zebrafish with more distractors throughout the simulation (zebrafish could have gotten 1-5 distractors) were more likely to die in the first half of their 100 trials but much less likely to die in the second half of the trials, which may have affected the Avg % of Death which was measured at the halfway point.

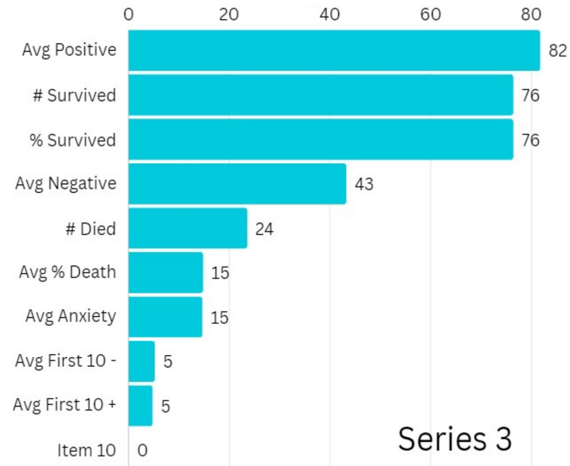

Figure 10. Figure of simulation 3

Looking at the results, the presence of the distractors likely affected how the zebrafish could make consistent, survival-enhancing decisions. This showed that additional complexity challenges the decision-making process and resulted in a decreased survival rate. Although still exhibiting a high rate of positive behaviors, a higher negative score compared to the previous iteration showed that the distractors increased the frequency of risky behaviors. Balancing anxiety levels with distraction likely made it harder to manage the stress function and aligns with real-life scenarios where distractions can make anxiety go higher than it should and impair decision-making. The zebrafish who were more likely to die in the first half with more distractors but less likely to die in the second half show that while distractors initially increase the likelihood of fatal mistakes, the zebrafish adapt to the presence of them, which likely increased focus and improved their survival chances. These results were significant, as they suggested that with sufficient exposure and experience, organisms can not only cope with distractions, but it helps improve their overall decision-making and adaptability. Understanding how distractions influence anxiety and behavior can lead to better strategies for coping with stress and maintaining mental well-being.

4. Related Work and Additional Discussion

These results returned significant insights into the mechanisms of learning, anxiety, and decision-making. When paired with related work, these can help us advance our understanding of these processes further in animal models and broader contexts.

With Simulation 2, anxiety and fear were introduced, which saw an increase in cautious behaviors and higher survival rates. This aligned with the research on adaptive nature of anxiety, which "suggests that anxiety serves an evolutionary function by heightening awareness and promoting safety-seeking behaviors" (Marks, 1987). These results underscored the role of anxiety as a protective mechanism while maintained within the optimal levels.

In Simulation 3, distractors were added, which made decision-making much more complex, and led to higher anxiety rates and mortality rates. Despite this, the zebrafish still adapted to distractors over time, showing how exposure to complex environments can enhance learning and focus. This worked with research on attentional processes, which showed that while performance may be impaired initially, strategies were present in organisms to mitigate effects over time (Lavie, 2005). This highlighted our adaptive capacity.

The introduction of distractors in Simulation 3 revealed how external stimuli influences zebrafish behavior and attention. Distractors initially increased anxiety levels and impaired decision-making, as evidenced by the higher mortality rates and increased frequency of negative behaviors compared to Simulation 2. However, as the simulation progressed, zebrafish began adapting to these distractions, prioritizing critical cues over irrelevant stimuli. This adaptation reflects an innate capacity to recalibrate focus in complex environments, aligning with previous findings on attentional processes in organisms (Lavie, 2005). The results suggest that while distractors can initially disrupt learning and survival strategies, repeated exposure may enhance resilience and attention selectivity, providing insights into how organisms optimize cognitive resources under stress. These findings could have implications for understanding how human attention systems cope with distractions, particularly in high-stress environments.

Future experiments involved with this would incorporate measurement that is more precise to focus and decision-making processes. Real-time tracking of neural activity could work with the simulation to show how these processes interact. MRI or optogenetics in similar animal models could also work to see the neural mechanisms that cause the results of this simulation to occur.

5. Comparisons with Other Methodologies

Methodology A was a tool that associates a neural stimulus with a biologically significant one, which retured results for how fish learn and store associative memories. This enhanced an understanding of neural circuits, which paralleled the use of classical conditioning paradigms within simulation built (Rehman, et al., 2003).

Methodology B underscored the importance of adaptive decision-making, making use of operant conditioning, which trained fish to perform specific tasks for rewards. This worked well with the observed changes in behavior due to anxiety, fear, and distractors in the simulation.

Methodology C used attentional control paradigms, which made zebrafish navigate competing stimuli, which validated the simulation's approach to studying attentional processes in behavior and survival, as the findings on how distractors affect anxiety levels, decision-making, and survival rates show how attentional control is relevant.

6. Conclusion

Despite the success of the current simulations, certain limitations exist. The first ten random choices to determine the results of the experiment may not fully represent how the beginning of an organism's behavioral processes work, as the first ten moves are still more probability to be influenced by reality. Additionally, the simulation primarily focused on reward and death, potentially overlooking other aspects of motivation. The third simulation's metric results though informative, might not measure the importance of focus, leading to less significance if paired purely with the metrics.

To address these limitations, further experiments with a more complicated algorithm for early-age behavior and large and more diverse simulation runs could provide a more comprehensive understanding of the attentional processes in behavior. The findings with anxiety and fear support the hypothesis that moderate levels of anxiety can enhance vigilance and promote survival by encouraging risk-averse behaviors. In the future, comparative studies could reveal universal principles of learning and adaptation, which would inform both basic research and practical application in fields such as psychology, education, and neurobiology. The work from this simulation provides a comparative model for studying learning and memory disorders in humans and could heighten awareness for work on those disorders which are not focused on in the modern age today.

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