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Article

Simulating natural selection via autonomous agents: Environmental factors create unstable equilibria

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SUMMARY

Natural selection is a vital process that forms the core of evolution of species. Through this process, advantageous traits of a species are passed down through generations, while disadvantageous traits tend to die off. In this study, we investigated the equilibria that the traits, speed and vision, approach as natural selection takes place. We aimed to test the hypothesis that there exists at least one equilibrium value for each of these traits that maximizes the lifespan of the species. We wanted to understand the extent to which natural selection can stabilize a particular trait for a species, and what factors influence this stabilization. It is already known that perfect stabilization in evolutionary games is not possible, but the mechanics of this destabilization have not been fully addressed from a biology standpoint. To address our hypothesis, we used a computer simulation to find relationships between various traits and their impacts on lifespan. We found that there are several confounding variables that influence the survivability of an organism other than the trait, such as the luck factor and the risk factor of a trait. We found that natural selection does not ever necessarily stop, because changes to the environment are continuously occurring, making it difficult or even impossible for equilibria to form. Our research demonstrated just how much natural selection is a continuous process rather than a predestined outcome as well as showed that further research must be conducted to explore these complex questions.

INTRODUCTION

Natural selection is a universal evolutionary strategy where successful traits are passed to future generations. Traits that are advantageous to the survival of a species are more likely to be passed on to the next generation, while less advantageous traits are less likely to be passed down (2). Traits are varied across a species due to random mutations, which results in some variations of the original trait to be more advantageous than others, thereby starting the cycle of selection over again. However, one question that is overlooked is whether there is a stopping point of natural selection. In other words, it is unknown if natural selection will result in the ideal, equilibrium value for any particular trait.

We hypothesized that there exists at least one equilibrium value for all traits with limiting factors, which maximizes lifespan. This hypothesis was supported by the Hardy-Weinberg equilibrium and a quasi-linkage equilibrium described by Kimura, although both examples are only valid under specific circumstances (3, 4). A limiting factor is a characteristic which limits growth of some attribute, in this case lifespan (5). For instance, a cheetah has a high speed of up to 75 miles per hour, yet quickly runs out of stamina in only 0.28 miles after moving at that full speed (6). This example illustrates a limiting factor of speed: stamina. It is possible that the faster an organism moves, the more stamina it consumes. In general, phenotypic plasticity has costs and tradeoffs with fitness (7). Another factor influencing the growth of a trait is the chance factor, which refers to how “lucky” the initial condition of the environment for an organism is (8). This can create a difference between the perceived benefit of an attribute’s value and the actual benefit of an attribute’s value. Finally, the risk factor is the amount of uncertainty a trait takes on (8). While the expected (net) benefit of an attribute may be high, in practice this means that higher risk can lead to a short-term unfavorable outcome, which would deter a species from that attribute value.

In this study we sought to identify equilibrium values for speed and vision and find a correlation between the traits and lifespan. In addition, we aimed to determine the reasons equilibria form at specific values. We found that traits may not actually have clear equilibria, as well as the fact that there are other factors that can determine the effectiveness of a trait, other than its survivability. In addition, we found that natural selection does not ever necessarily “stop,” because changes to the environment are continuously occurring, making it difficult or even impossible for equilibria to form. In some cases, the rapidity of changes in the environment can be too quick for evolution to keep up, leading to the potential extinction of a species (9). Our research demonstrated how much natural selection is randomized rather than predestined, and just how strong other factors such as chance is compared to naturally forming equilibriums.

RESULTS

In order to examine the relationship between traits and lifespans, we ran a simulation of two competing species. Using a simulation allowed us to control environmental features, such as the number of organisms present, and easily measure trait values and lifespans. We found there was a moderately strong correlation between generations (time) and vision. This implies that as the number of generations increases, so too does vision (**Figure 1**). We can also observe the relationship between vision and lifespan for rabbits. While there is a positively sloped trendline, only 21.8% of the variation in rabbit lifespan is accounted for by the model, thus demonstrating the very weak, but statistically significant, correlation between vision and lifespan ($p < 0.001$) (**Figure 2**).

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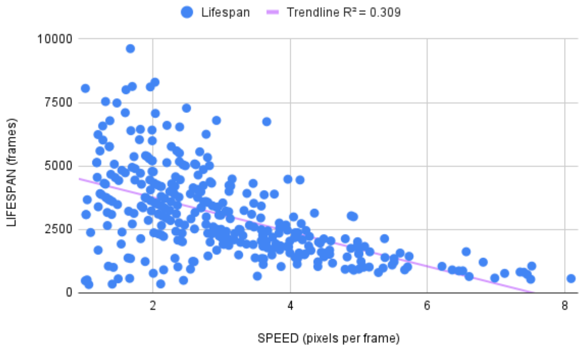

Figure 1. Increasing rabbit generations results in improved vision. Line graph and trendline for one representative simulation illustrating the way vision changes over generations of rabbits (n=1). Computer simulation of natural selection created environment with 50 carrots, 15 rabbits, and 17 foxes which was then used to record the vision value of the "best" rabbit of each generation. R^2 = 0.777.

We also ran a similar experiment for speed, measured in pixels per frame. Rather than mutating vision for the rabbits, we mutated the speed attribute instead. We then measured and recorded the attributes for speed and lifespan of the best rabbit for each generation.

Over the course of several generations, the speed attribute tended to be erratic in its evolution, never fixating at one value, but rather fluctuating frequently (**Figure 3**). This was likely due to the randomness of the placements of predators, other rabbits, and carrots. However, there was a very clear trend in the relationship between the speed of rabbits and their lifespan. As speed increased, the average lifespan of a rabbit became significantly shorter (p < 0.001), and this correlation was statistically significant (**Fiure 4**).

Overall, both the vision and speed traits significantly impacted lifespan, albeit in different ways. Increasing vision tended to improve lifespan, while increasing speed tended to worsen lifespan. However, both traits also fluctuated differently over the course of several generations. While vision did not fluctuate much over generations, speed fluctuated greatly.

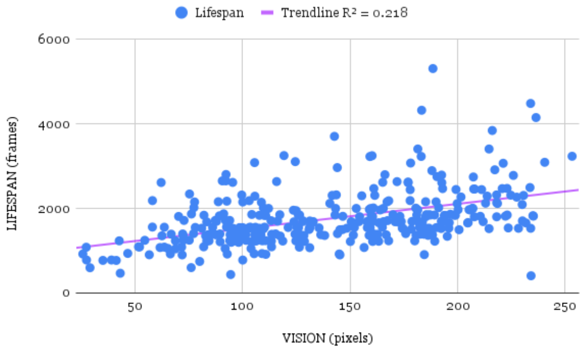

Figure 2. Increasing vision moderately improves lifespan. Scatterplot illustrating the relationship between vision and lifespan of rabbits across all trials (n = 1). Computer simulation of natural selection created environment with 50 carrots, 15 rabbits, and 17 foxes which was then used to record the vision value and lifespan of the "best" rabbit of each generation. p < 0.001 for the Pearson correlation coefficient.

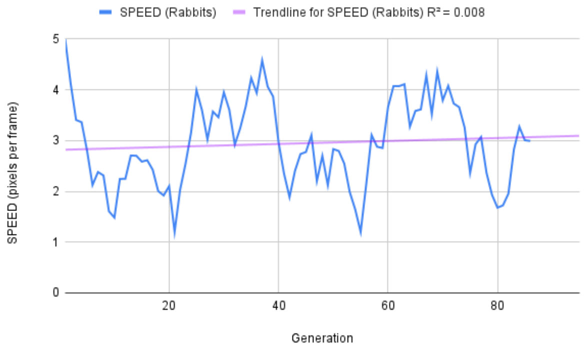

Figure 3. Increasing rabbit generations have almost no correlation with speed. Line graph and trendline for one representative simulation illustrating the relationship between generations and rabbit speed (n = 1). Computer simulation of natural selection created environment with 50 carrots, 15 rabbits, and 17 foxes which was then used to record the speed of the "best" rabbit across generations. R^2 = 0.008.

DISCUSSION

In the experiment for determining the impact of vision on lifespan, we determined that vision has very little influence on the lifespan of the rabbits. While there was a slight upwards trend in the relationship between vision and lifespan and evidence of a correlation, the low value of the coefficient of determination demonstrates how weak this correlation is. We can reasonably conclude, therefore, that vision does not meaningfully impact the survivability of the rabbits in this scenario. There was no evident equilibrium for vision, as its value did not seem to impact lifespan much. However, it is plausible that under different conditions, vision could be a much stronger factor in determining lifespan. Similar studies investigating the effects of natural selection on vision show that an increase in the quality of vision (trichromacy) is naturally selected (9). Also, the limiting factor hypothesized for vision, the stress of constantly avoiding predators that are visible, could still very well be a possibility. A larger number of visible predators could loosely relate to cognitive overload, or information overload paralysis, which could then result in increased "stress," but further research is needed to draw concrete conclusions (10). If the number of predators were increased in the simulation, each rabbit would, on average, encounter more foxes, which would likely limit the benefit of higher vision more. Another possibility is that genetic drift prevented an equilibrium from forming; a possible cause of this drift could come from a lack of rabbits in the simulation, which would reduce the probability that the best rabbit was selected due to its favorable attributes rather than through chance (11). Finally, the randomization of starting placements and movements may have been a contributor to the large variation in lifespans, similarly to how a "luck factor" would add uncertainty. For small populations, like the ones simulated, this luck factor would be quite important, since individual organisms have a higher overall probability of becoming the best through pure coincidence.

In the experiment for determining the impact of speed on

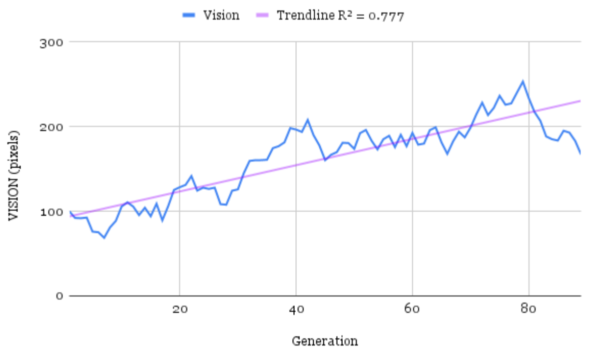

Figure 4. Increasing speed results in worsening lifespan. Scatterplot illustrating the relationship between the speed and lifespan of rabbits across all trials (*n* = 1). Computer simulation of natural selection created environment with 50 carrots, 15 rabbits, and 17 foxes which was then used to measure and record speed and lifespan of the "best" rabbit for each generation. $p < 0.001$ for the Pearson correlation coefficient.

lifespan, we determined that speed had a relatively strong influence on the lifespan of the rabbits. There was a clear downwards trend in the relationship between lifespan and speed; on average, it was more favorable to have a decreased speed and conserve energy than it was to have a high speed and sacrifice energy. However, the phrase "on average" is important here, since as speed decreases, lifespan tends to deviate more from the trendline. This fact implies another factor that is overlooked in natural selection: the risk factor. Even though a trait might be beneficial in general, it could be prevented from being passed on due to unlucky environmental factors. As such, certain traits appear to be riskier than others, with high benefits if it succeeds, and high costs if it fails. This idea is illustrated through the large deviations observed from the relationship between the lifespan of rabbits and low speeds. The riskiness of a trait was an important facet of natural selection that may have been overlooked within the study initially. In the context of the simulation, this makes sense; since the number of foxes was rather high, it would certainly be risky to reduce speed and hope to avoid a fox. On the other hand, if a rabbit was able to avoid encountering foxes, it would be able to survive for a long time due to its conserved energy. Fisher's fundamental theorem of natural selection supports this idea: the rate of increase in the mean fitness is exactly equal to the additive genetic variance (12). In other words, the more genetic variation there is, the faster the mean fitness of a population changes. However, this risk factor is currently a hypothesis that should be confirmed in future studies.

Finally, the lack of clear equilibria in both experiments suggests that longer and greater numbers of simulations should be conducted, as it is possible that an equilibrium simply did not have enough time to form. Additionally, measures to reduce the complexity of the simulation, such as removing the carrots entirely, could reduce the presence of confounding variables, thus increasing the precision of the data collected in future experiments. Furthermore, the size of the simulation should be increased to reduce the effects of chance to ensure that the probability of an organism becoming the "best" through random chance is lower.

Our research illustrates how complex the process of natural selection is in practice. While its definition is simple, there are a multitude of things that must be considered when evaluating its effects, such as chance, the risk factor, and the relative importance of a trait to survivability. In order to model the effects of natural selection and make predictions, it is of the utmost importance to keep these factors in mind. The differences in variation of lifespan across different intervals of trait values and the correlation between lifespan and the trait itself all demonstrate how many factors can influence natural selection, even when there is only one trait present to mutate. These results indicate that when modeling evolutionary processes, it is imperative to understand that even simplified models that exclude several real-world factors that prevent the formation of an equilibrium and include repetition are subject to chance occurrences.

MATERIALS AND METHODS

The simulation was run on a web browser via JavaScript ES6, and data was collected via console messages containing information about each generation. Each datum contained information about the generation number, the values for the best rabbit's traits, and the lifespan of the best rabbit. The data for the speed and vision traits were collected individually, and two relevant graphs were plotted for each. The first was a trait versus generation line chart, and the second was a lifespan versus trait scatterplot. The coefficient of determination of both was calculated, and a p-value was found. The full script can be found at https://github.com/adityamkk/Evolution.git.

For each experiment, we used a simulation to model evolution over several generations in response to the simple yet common predator-prey relationship. Foxes represented the predator, rabbits represented the prey, and carrots represented the prey's energy source. In our simulation, both species had a similar set of traits: speed, mass, vision radius, and energy, as well as behaviors that control escaping or catching prey, such as bursting (e.g., a cheetah). If an animal's energy reached 0 or it was eaten, it died. Animals can gain energy by eating their prey: rabbits eat carrots, and foxes eat rabbits. After all the animals in a generation die, the traits of the animal that survived the longest from each species are used to construct the traits of the next generation, after modifying each of them slightly for each new organism to account for mutations. In each simulation, 50 carrots, 15 rabbits, and 17 foxes were randomly placed within the environment. These amounts were chosen after repeated observation of generations of rabbits and foxes and adjusting values; We determined that these quantities would be the most likely to create conditions in which an equilibrium could form. If there were too many rabbits or foxes, then food would run out too quickly. If there were too few, then there would not be enough competition for an equilibrium to emerge. A rabbit would neither be able to ignore predators entirely nor devote all of its energy to running from them: it would have to reach a compromise between those strategies (hence, the formation of an equilibrium).

In order to accurately model the impact vision has on lifespan, foxes were set to not evolve at all, and rabbits would only evolve vision (no other traits would change across generations). For this experiment, we recorded the values for both vision, measured in pixels, and lifespan, measured in frames, from the "best rabbit"— the rabbit that survived for

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the longest period in a generation. We chose these measures of rabbit vision and lifespan rather than other measures (e.g., average rabbit vision) to indicate the baseline statistics of rabbits in the next generation. The simulation was run four times since we believed that that amount would be sufficient to determine if a pattern emerging from a single simulation was a correlation or was simply coincidence. Each simulation was run for 80 generations to ensure that no trends that emerged over time were due to coincidence.

To run each of the simulations, the index.html file was opened on the browser (Google Chrome). Afterwards, the green buttons that toggled traits not related to the trait measured were turned to false, and the simulation was run. After approximately 15–20 minutes, and about 70–90 generations had been simulated, the data printed to the console was collected and processed. Different simulations had different numbers of generations simulated.

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