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Visualizing search behavior with adaptive discriminations

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ABSTRACT

We examined different aspects of the visual search behavior of a pigeon using an open-ended, adaptive testing procedure controlled by a genetic algorithm. The animal had to accurately search for and peck a gray target element randomly located from among a variable number of surrounding darker and lighter distractor elements. Display composition was controlled by a genetic algorithm involving the multivariate configuration of different parameters or genes (number of distractors, element size, shape, spacing, target brightness, and distractor brightness). Sessions were composed of *random* displays, testing randomized combinations of these genes, and *selected* displays, representing the varied descendants of displays correctly identified by the pigeon. Testing a larger number of random displays than done previously, it was found that the bird's solution to the search task was highly stable and did not change with extensive experience in the task. The location and shape of this attractor was visualized using multivariate *behavioral surfaces* in which element size and the number of distractors were the most important factors controlling search accuracy and search time. The resulting visualizations of the bird's search behavior are discussed with reference to the potential of using adaptive, open-ended experimental techniques for investigating animal cognition and their implications for Bond and Kamil's innovative development of virtual ecologies using an analogous methodology.

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1. Introduction

Understanding how animals solve discriminations has been at the heart of the study of learning since its inception (Köhler, 1925; Thorndike, 1898; Tolman and Honzik, 1930). An important theoretical concept for understanding any discrimination revolves around the idea of a *solution space*. For any discrimination, there is a multidimensional space that represents the different potential operations used by an animal to solve and perform a specific task, their likelihoods, and potential order of occurrence. These solutions operate on the features available within a task and consist of those cognitive operations and processes by which stimuli come to differentially control behavior. Because understanding these complex psychological spaces is critical for a complete account of animal behavior in the real world, the development of procedures to explore, map, and analyze them is important. The controlled parametric manipulation of experimental variables has been one time-honored means of doing so. In recent years, however, other computational approaches have offered new possibilities for investigating these questions. Genetic algorithms represent one powerful type of this approach.

Genetic algorithms (GAs) are a form of optimization procedure that can do an open-ended search of a problem's potential solution(s). GAs have had an increasingly widespread impact across different areas of science and engineering, including biology, economics, bioinformatics, robotics, and machine learning. We think these and associated evolutionary methods have substantial potential for the investigation and identification of the cognitive processes and operations engaged by animals in discriminative settings. Their application and impact in psychology has only been nominal and their utilization for the experimental control and measurement of either human or animal behavior limited.

We think these adaptive procedures hold a number of advantages. First, they are ideal for quickly searching large multivariate, parametric spaces. This allows the analysis of situations that are much closer in their complexity and dynamics to the real world than most experimental settings. Second, they are open-ended, automatic, and make few prior assumptions about the nature of the space or its appropriate solution. Thus, any demand characteristics imposed by the procedures or the shape of the problem space are reduced. Third, by their fundamental organization, GAs are temporally extended in nature allowing the possibility to observe dynamics and changes in cognition over time. Fourth, they are subject-driven. Because the selection is done by the animal's

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behavior, the animal has more direct control of the form of the discrimination. In one sense, GAs causes the procedure to "adapt" to the animal rather than vice-versa. Finally, by reconceptualizing how we can approach the study of animal behavior, it generates new ideas and theories about the best way to understand how animals interact with the environment.

In an innovative and initial application of a GA to the study of animal behavior, Bond and Kamil developed a "virtual ecology" to investigate the evolution and maintenance of polymorphism in prey species (Bond, 2007; Bond and Kamil, 1998, 2002, 2006; Kamil and Bond, 2001, 2002). In these studies, blue jays searched for and detected different kinds of digital "moths" on a computer screen over a series of trials. The visual properties of different "species" were then controlled by a set of underlying *parameters or genes* that controlled their *phenotypic* appearance and structure. Analogous to the real world, if a moth was detected on the display screen, it was "eaten" by the jay and its genes did not contribute to the next generation of possible prey items used to create future trials. Thus, over trials, the featural composition of the moth stimuli gradually transformed because of the differential selection behavior of the blue jays.

Using this GA technique, Bond and Kamil examined the role of predator-generated crypsis and frequency-dependent selection on the polymorphic nature of prey populations. They found that the jays caused the prey populations to become perceptually more cryptic, with a graded relationship between detection time and reproduction. Furthermore, the prey items became phenotypically more diverse when presented on varying backgrounds. The jays demonstrated a tendency to select those prey items that were more similar to recently encountered items. This "overselection" of certain moth phenotypes was beyond what would be expected given their density in the underlying population. This suggests that that sequential selective attention or a search image for different visual features of the moths may have been employed by the blue jays. The conjoint operation of these aspects of blue jays' visual cognition resulted in the dynamic maintenance of a polymorphism among "moth" stimuli within the virtual ecology. This research elegantly demonstrated how adaptive techniques can be used to understand how cognition functionally influences the evolution and structure of the natural world.

Because of its potential, we have recently been employing a GA to investigate visual cognition in a different bird species, the pigeon. While we have several projects ongoing looking at different phenomena using this technique, our first project of this type investigated how pigeons solve a visual search problem in which the GA was continuously employed to govern the evolution and organization of the trials over sessions (Cook and Qadri, 2013). On each trial, the animal had to accurately locate and peck an intermediate gray *target* element from among a variable number of surrounding darker and/or lighter *distractor* elements of varied spacing. The displays were generated from parametric variables or genes that controlled distractor number, element size, shape, spacing, target brightness, and distractor brightness. The GA resulted in the composition of the visual displays evolving because of the pigeon's differential accuracy with the large number of diverse trials that were possible from the different combinations of display genes. One important difference from Bond and Kamil's GA procedure is that we selectively retained the genes from successful target identification displays and eliminated those associated with incorrect responding, whereas in their procedure a successful search by the blue jays resulted in that display's genes being eliminated from reproducing and the resulting population. The differences produced by such "positive" versus "negative" selection operators are an important area for exploration with GAs in the future.

Cook and Qadri (2013) reported two experiments examining how a pigeon's selection behavior dynamically altered displays within the search task. In their experiments, the size of the elements and the number of distractors in the displays were the principal factors determining the pigeon's search accuracy. The brightness of the distractors, the shape of the elements, and the relative spacing of items on the display made secondary and sometimes variable contributions. This outcome suggested the existence of a set of values within the larger multivariate stimulus space of possible displays that were best given the bird's solution to the task. One way to conceptualize this solution is as a set of cognitive operations that form a type of stable psychological "attractor". This attractor is the pattern or solution from within the larger multidimensional solution space that represents the perceptual, cognitive, and decisional processes currently brought to bear on the task by the animal. By examining the different stimuli within the stimulus space that were differentially affected by this attractor, one can infer the nature of the operations comprising the implemented solution.

To test for the existence of such an attractor in the previous experiments, we tested the bird from three different sets of randomized initial conditions and from one set of controlled initial conditions. These initial conditions represented the beginning seed values for the different genes during the first session of any phase. We found that the bird's selection behavior resulted in the visual search stimuli repeatedly evolving towards the same point in the performance space regardless of the initial conditions or starting values of the genes. This suggests the pigeon employed the same visual search solution during each iteration of the GA.

The current experiment focused on better understanding the stability and shape of this attractor. This was accomplished by capturing a high quality portrayal of the bird's discriminative behavior over the entirety of the stimulus space tested as collected over an extended period of testing. In the prior experiments, we concentrated on tracing out the trajectory of the bird's ongoing selection and resulting alteration of the gene populations. For that purpose, a considerable proportion of the daily trials were derived from variations of previously successfully displays. This resulted in a reduced sampling of the entire stimulus space, which prevented us from identifying the diffuse influences of the attractor. Further, because we reset the discrimination several times, we did not collect observations regarding the attractor's stability over any extended period of time. Thus, it is unknown if the bird would stay in the vicinity of its initial solution or would or could the bird shift its solution with experience?

In the current test, we altered the GA procedure to examine better the bird's search behavior across the entire set of stimuli by increasing the proportion of randomly generated trials within a session sixfold. As a consequence, 67% of trials within a session were randomly generated from the entire range of genotypic values rather than just the 10% "sampling rate" used in the previous experiments. This increase in the proportion of randomly generated trials tested the entire stimulus space more thoroughly than was possible before. To measure of the stability of this solution, we tested the pigeon for 200 60-trial sessions. This extended period of testing resulted in 8000 random and 4000 selected trials for analysis. Given this large collection of data, another of our goals for this experiment was to map and characterize the shape of the attractor used by the bird. Better visualizing its structure and organization over the entire stimulus space should provide a better understanding of the bird's solution and its influence on selection and performance.

2. Method

2.1. Animal

A male White Carneaux pigeon (*Columba livia*) was tested. This bird was familiar with the task and procedures (Cook and Qadri,