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Authors
Lomas, Dennis R.
Tsotsos, John K.

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The search image hypothesis in animal behavior: its relevance to analyzing vision at the complexity level *

Dennis R. Lomas
John K. Tsotsos †
Department of Computer Science, University of Toronto
Toronto Ont. M5S 1A4
email: lomas@vis.toronto.edu tsotsos@vis.toronto.edu

Abstract

We show how a concept from animal behavior, the visual search hypothesis, is relevant to complexity considerations in computational vision. In particular we show that this hypothesis is an indication of the validity of the bounded/unbounded visual search distinction proposed by Tsotsos. Specifically we show bounded visual search corresponds to a broad range of naturally occurring, target-driven problems in which attention alters the search behavior of animals.

Introduction

In *Analyzing vision at the complexity level* Tsotsos (1990) develops a method for understanding biological visual search processes, an immeasurably difficult reverse engineering problem. He maintains that, since visual search aside from such things as direct sensing of light on the retina is fundamentally a computational task, any model or theory for human or animal visual search must satisfy computational complexity constraints.[1] This means that algorithms in computationally-based models or theories must compute in reasonable time. In the terminology of algorithmic complexity theory vision algorithms that mimic human or animal visual search need to be *tractable* rather than *intractable*.[2] Moreover such models or theories need to accomplish their tasks with the known resources for visual processing in the brain. Furthermore, since general visual search is an intractable problem,[3] such complexity considerations are not just a detail to contend with at implementation but need to inform each stage of model or theory development.[4]

Using this approach he develops (by placing constraints on such things as the type of objects that can be recognized and the number of features that can be used in recognition) a model for human and animal vision that satisfies first order complexity constraints.

Tsotsos begins his analysis by establishing a fundamental dichotomy for visual search problems between *unbounded visual search* and *bounded visual search*. In *unbounded visual search* "either the target is explicitly unknown in advance or it is

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†Fellow of the Canadian Institute for Advanced Research

[1] For a brief overview of complexity theory see sections 1.3 and 1.4 in *Analyzing vision at the complexity level* (Tsotsos 1990).

[2] A tractable algorithm performing visual search on an image can be viewed as one whose time requirements can be expressed as a polynomial function of the pixels required to represent the image whereas for an intractable algorithm time requirements in the worst case are an exponential function of the pixels required to represent the image.

[3] Tsotsos suggests that general visual search is intractable because it contains as a subprogram an intractable problem: *unbounded visual search* (see below for a definition of *unbounded visual search*).

[4] Tsotsos also uses minimization of cost, a consideration not relevant to this contribution.

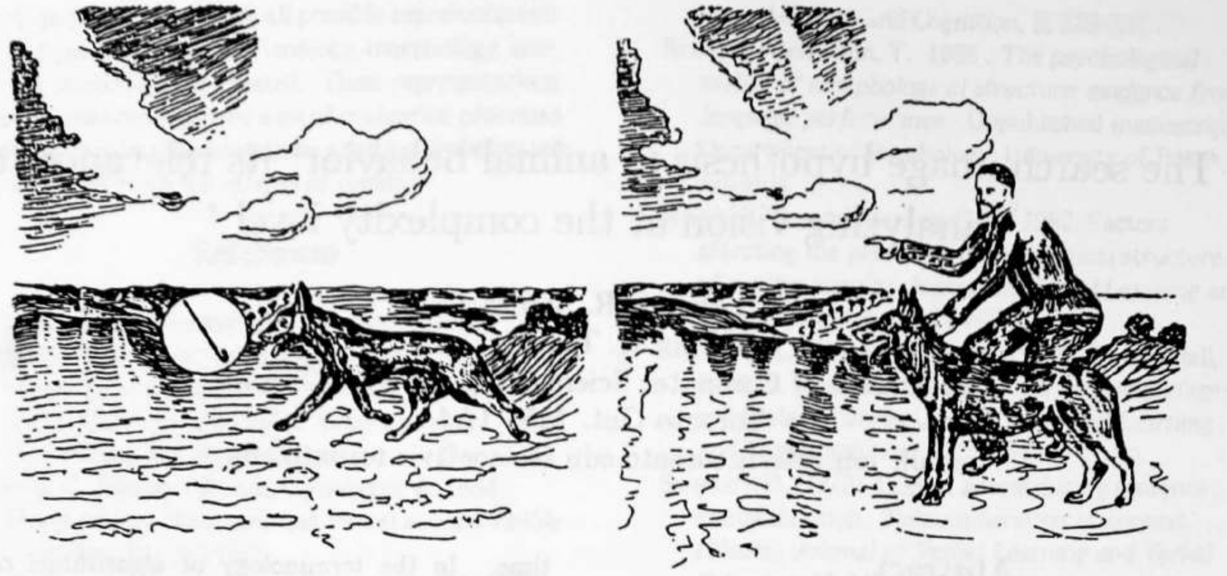

Figure 1: The dog and his search image. "When the master orders his dog to retrieve a stick, the dog, ...has a quite specific search image of the stick." Jakob von Uexküll who coined the phrase 'search image.' This figure appeared in an anecdotal article by Uexküll (1934), *A stroll through the worlds of animals and men.*

somehow not used in the execution of the search" while in ***bounded visual search*** "the target is explicitly known in advance in some form that enables explicit bounds to be determined that can be used to limit the search process." The dichotomy arises from a complexity analysis of the two problems:[5] ***unbounded visual search*** is potentially intractable, ***bounded visual search*** is tractable.

Moreover, he suggests "because actual psychological experiments on visual search with known targets report search performance as having linear time complexity and not exponential, the inherent computational nature of the problem strongly suggests that attentional influences play an important role."

The purpose of this contribution is to show that a concept from animal behavior, the ***visual search hypothesis***, introduced some thirty years ago, confirms the validity of dividing visual recognition into the categories of ***unbounded visual search*** and ***bounded visual search***.[6] Experiments and observations of animal behaviorists involved in developing and testing the ***visual search hypothesis*** indicate that ***unbounded visual search*** is an intractable form of visual search. Additionally, these studies suggest ***bounded visual search*** corresponds to a broad range of naturally occurring, target-driven problems in which attention alters the search behavior of animals in the studies.

[5] an analysis undertaken in a mathematical, formal setting

[6] See the exchange between Paul R. Kube and John Tsotsos for an interesting discussion of this claim. (See commentary on Tsotsos's ***Analyzing vision at the complexity level*** (Tsotsos 1990) and (Tsotsos 1991)).

The search image hypothesis

The ***search image hypothesis*** was first formulated by Tinbergen (1960) making use of the term 'search image' coined by Uexküll (1934). Birds observed by Tinbergen dramatically fail to detect the presence of novel prey even though its dietary appropriateness and abundance warrants predation. Detection of the prey commences only after chance encounters. He suggested these encounters prompt the formation of a search image that subsequently enables the predator to detect the prey. (Pietrewicz and Kamil 1979) Of course such observations fall short of establishing the hypothesis by today's experimental standards. In the last twenty years in the course of designing and performing numerous experiments, animal behaviorists have more precisely formulated the ***search image hypothesis*** and tested it against alternate explanations of predator behavior.

In animal behavior literature (for example, see Pietrewicz and Kamil (1979)) the *search image hypothesis* explains behavioral change by postulating a perceptual change in the ability of a predator to detect prey. This perceptual change occurs because the predator has learned to recognize prey (formed a search image) where typically the prey is cryptic (the background and the prey are similar[7]). Thus confronted with prey in a cryptic setting the predator has been able to learn, and to attend selectively to, cues that enable it to distinguish the prey from the background.[8]

The formation of the search image directly influences the predator's ability to see the prey. Moreover, it operates in conjunction with attention mechanisms.

Search image hypothesis: Confirmed in experimentation

In the last twenty years many experiments have confirmed the *search image hypothesis*. In particular the work of Dawkins in 1971 warrants a brief review since it demonstrated for the first time in an experimental setting the validity of that hypothesis and set the stage for subsequent experimental work. Dawkins (1971a) noted that "Tinbergen's basic idea in postulating it (the *search image hypothesis*), namely, that birds become better able to perceive cryptic prey as their experience of it increases, is of great interest. The purpose of this paper is to show that changes in a bird's ability to perceive its cryptic prey do indeed occur, and may be responsible for major changes in its feeding behavior."

Dawkins observed chicks taking grains of rice from backgrounds of stones glued onto hardboard. The grains were either green or orange and could be either the same colour as the background, in which case they were called cryptic, or a different colour from the background, in which case they were called conspicuous. Dawkins found that most chicks took grains more slowly at the beginning of both tests but that the chicks were much less able initially to detect cryptic grains. "It would seem," Dawkins remarked, "that chicks did not take cryptic rice at first because they did not see it. ..."

The experiments showed the chicks' initial inability to detect cryptic food despite almost certainly looking at it. "...it seems reasonable to suggest," Dawkins argued, "that their subsequent improvement in detection is due to some sort of central perceptual change rather than to more peripheral modifications to vision such as reorientation of the head and eyes."

In a subsequent set of experiments Dawkins (1971b) first presented chicks with grains of one colour and type and then presented them with a choice of grains in another setting, e.g. after cryptic orange grains the chicks are presented with a choice between conspicuous green grain and cryptic orange grain. The experiments thus tested for an attentional mechanism associated with the development of a search image. "...the results," Dawkins notes, "are ...compatible with the idea that chicks become better able to see cryptic grains when they have just been eating other cryptic grains than after eating conspicuous ones. They may temporarily 'shift attention' on cues that enable them to detect such grains."[9]

Dawkins experiments were repeated in 1985 by

[7] I.e. an organism is cryptic if its colour pattern is a random sampling of the background against which predators usually see it. (Lawrence and Allen 1983).

[8] The cryptic prey may be novel or familiar. In the latter case, the formation of a search image signifies "a change in the ability to detect cryptic, familiar prey as a function of recent encounters with that prey." Pietrewicz and Kamil distinguish this case from the former by calling the former where novel,cryptic prey are involved the development of a *specific* search image (Pietrewicz and Kamil 1979).

[9] Like subsequent search-image-hypothesis experiments Dawkins set up the experiments to exclude other explanations of observed behavior such as:

- learning to visit a particular place to find food
- learning to look in a particular type of place to find food
- alteration of the search path to increase the chances of encountering prey
- learning to handle prey more effectively
- preference or avoidance of a prey over others that is independent of the predator's ability to see the different types
- learning of specialized hunting techniques by particular individuals

(taken from Lawrence (1983))

Lawrence (1985) on blackbirds. In reference to experiments testing detection of cryptic prey, corresponding to Dawkins' first set of experiments, Lawrence observes: "the simplest explanation is that the birds failed to see the cryptic prey at first; the alternative (and more unlikely) explanation is that the birds (for some reason) found prey unacceptable only under cryptic conditions. ...The high frequency of background-directed pecks during the first third of the feeding sessions on cryptic prey suggests that initially the birds failed to see the prey." Moreover, he argues that the results of all his experiments "lend support to the idea that wild predators acquire search images as a normal part of their foraging behavior."

Over the past two decades the *search image hypothesis* has similarly been confirmed. These studies include: Murton's (1971) work with wood-pigeons (*The significance of a specific search image in the feeding behavior of the wood-pigeon*); Pietrewicz and Kamil's (1979) study with jays (*Search images and the detection of cryptic prey: An operant approach*); Bond's (1983) experiments with pigeons (*Visual search and selection of natural stimuli in the pigeon*); and Gendron's (1986) work with quail (*Searching for cryptic prey: evidence for optimal search rates and the formation of search images in quail*).[10] An example of recent work on the *search image hypothesis*[11] is Blough's (1989) experiments with pigeons (*Attentional priming and visual search in pigeons*).

The accumulated research confirming the *search image hypothesis* together with the fact that originally it arose from observations in natural settings indicates the robustness of the phenomenon. The findings suggest, as Bond (1983) suggested for his work, "the operation of a robust and pervasive cognitive process, one that may well be characteristic of visual search for cryptic stimuli in other species."

[10] After the publication of Gendron's paper Guildford and Dawkins (1987) claimed that the experiments on the *search image hypothesis* to that time had not sufficiently accounted for an alternative hypothesis to explain experimental observations: a decreased search rate to enhance detection of cryptic prey accounts for the observed behavior. However the major prediction of this hypothesis was contradicted in subsequent experiments by Blough (1989).

[11] Blough suggests, "In current terminology, a search image might be described as a representation activated by an exposure sequence." (Blough 1989)

What the search image hypothesis shows

It is evident that *unbounded visual search* is a form of visual search prevailing before a predator forms a search image:[12] the predator is searching for prey, prey that is readily available but its presence does not guide the search for food. Moreover, *bounded visual search* corresponds to behavioral modifications induced by the formation of a search image, behavioral modifications that are likely accompanied by some form of attention. Thus, the *search image hypothesis* shows the validity both of the unbounded/bounded distinction in visual search and of the suggestion that attentional elements enable *bounded visual search*. Furthermore, the robustness of the *search image hypothesis* and the fact that is has a significant domain - the search for cryptic grain - one that occurs in natural settings, suggests the unbounded/bounded distinction in visual search is a natural distinction at least for some significant aspects of vision.

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[12] as the result, for example, of chance predation or relaxation of attention to another prey

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