



Hybrid foraging search: Searching for multiple instances of multiple types of target



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ABSTRACT

This paper introduces the “hybrid foraging” paradigm. In typical visual search tasks, observers search for one instance of one target among distractors. In hybrid search, observers search through visual displays for one instance of any of several types of target held in memory. In foraging search, observers collect multiple instances of a single target type from visual displays. Combining these paradigms, in hybrid foraging tasks observers search visual displays for multiple instances of any of several types of target (as might be the case in searching the kitchen for dinner ingredients or an X-ray for different pathologies). In the present experiment, observers held 8–64 target objects in memory. They viewed displays of 60–105 randomly moving photographs of objects and used the computer mouse to collect multiple targets before choosing to move to the next display. Rather than selecting at random among available targets, observers tended to collect items in runs of one target type. Reaction time (RT) data indicate searching again for the same item is more efficient than searching for any other targets, held in memory. Observers were trying to maximize collection rate. As a result, and consistent with optimal foraging theory, they tended to leave 25–33% of targets uncollected when moving to the next screen/patch. The pattern of RTs shows that while observers were collecting a target item, they had already begun searching memory and the visual display for additional targets, making the hybrid foraging task a useful way to investigate the interaction of visual and memory search.

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1. Introduction

We spend our days looking for pens lying on the desk, socks hiding in the laundry, pedestrians crossing the street, and so forth. In the lab, this diversity of visual search tasks is generally reduced to a search for a single target that may or may not be present amidst some number of distractor items (Wolfe, 1998, 2015). There has been much less exploration of search tasks with multiple types of possible targets or with multiple instances of targets in the same search scene. Search for any of several target types is characteristic of many real world search tasks. Search for the four items on your shopping list for dinner would be an example. If the set of possible targets is held in memory, then these are tasks that have both a memory search component and a visual search component. Schneider and Shiffrin (1977) named these “hybrid searches”.

Schneider and Shiffrin studied hybrid searches with small numbers (1–4) of alphanumeric items in both the visual set and the memory set. Wolfe (2012) took advantage of the ability of human observers to memorize large numbers of objects (Standing, Conezio, & Haber, 1970; Brady, Konkle, Alvarez, & Oliva, 2008) in order to study hybrid search with much larger memory set sizes. Experiment 2 of Wolfe (2012) had observers searching for any of 100 possible targets and Wolfe, Boettcher, Josephs, Cunningham, and Drew (2015) extended this to over 500 items.

Results of these experiments have a characteristic form over many replications and variations. As is typical in visual search experiments, response times (RTs) are a linear function of the visual set size. However, RTs do not rise linearly with memory set size. Instead, RT is a linear function of the log of the memory set size. This logarithmic relationship may be the result of properties of a diffusion process of target identification (Leite & Ratcliff, 2010). In diffusion accounts of search, information about a particular item is accumulated and the item is identified when the information reaches a decision boundary. Since accumulation is noisy,

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there is the possibility of a false positive response if the boundary is set too low. If there are multiple possible targets and, thus, multiple accumulators, thresholds must be set higher because of the increased chance that one boundary will be incorrectly crossed. The higher position of the boundary produces a longer RT and this increase is logarithmic if error rates are held constant. This pattern of linear $RT \times$ visual set size functions and log-linear $RT \times$ memory set size functions is seen for sets of unique objects (Wolfe, 2012), categories of objects (e.g., are there any animals, coins, plants, or flags?) (Cunningham & Wolfe, 2014), and lists of words (Boettcher & Wolfe, 2015).

If we turn from multiple types of targets held in memory to multiple instances of one target type present in the visual world, we enter the realm of foraging tasks. Foraging tasks have been studied most extensively in animals (Stephens & Krebs, 1986) but there are many human search tasks in which the number of targets is unknown and potentially large. Such tasks might include searching a medical image for signs of cancer or picking berries off of a succession of raspberry bushes. Collecting information from the internet has been described as a foraging task (Pirulli, 2007) as have tasks like searching memory for specific concepts or words (e.g., name as many animals as you can in 30 s) (Hills, Jones, & Todd, 2012). Indeed, foraging seems to be a ubiquitous aspect of our cognitive architecture (Hills & Dukas, 2012).

The primary metric of interest in foraging studies is the “patch leaving time”. Targets are found at some rate and collecting those targets makes them scarcer. Therefore, the rate of target acquisition slows down. Eventually, it is not worth continuing to collect targets from the current patch and you should move to the next patch. Moving comes at a cost since you cannot collect more targets until you reach the next patch, so it behooves you to adjust the time spent in each patch so as to maximize your overall target collection rate. The most influential model of average patch leaving behavior is the Marginal Value Theorem (MVT) (Charnov, 1976). MVT holds that the forager should leave the current patch when the rate of return for the patch drops below the average rate of return for the task. Wolfe (2013) looked at the behavior of human observers collecting red ‘berries’ on a computer screen. Observers’ data was consistent with MVT for simple situations such as an endless collection of essentially identical patches. Behavior systematically deviated from MVT predictions when the world became more complicated, for example, when patch quality varied dramatically from patch to patch. Hutchinson, Wilke, and Todd (2008), among others have also reported systematic deviations from optimality in human foraging behavior. In their experiment, for instance, observers were “fishing” on the computer in a succession of fishing holes for fish that could not be seen on screen. The time at which they left one patch for the next was overly dependent on the time of the most recent capture of a fish.

Even when it is a good approximation of the average data, MVT is often unlikely to be a description of what a forager is actually doing on a trial-by-trial basis. Foragers probably do not have particularly accurate estimates of the average rate of return, and their current rate of return can drop to zero while searching for the next target without prompting an immediate departure for the next patch. “Potential value theory” deals with these problems by predicting quitting time using the forager’s assessment of what remains in the patch based on an initial estimate of the number of targets present (McNamara & Houston, 1985). Such a model can incorporate a Bayesian updating component that allows the initial estimate of the number of targets to evolve during a trial. Thus, an initially high estimate might be lowered if, for example, it took a surprisingly long time to find the second target (Cain, Vul, Clark, & Mitroff, 2012).

Now consider another search task, illustrated in Fig. 1 and familiar to children and parents in many lands. Preparing for the

battle of the Lego® alligators and the astronauts requires search for all of the instances of each of the targets, shown at the top of the figure. Of course, all of the Lego® building bricks are jumbled into a big box.

This is a hybrid search with a memory set size of four and a large visual set size. It is also a foraging task since you are looking for an unknown number of targets in this patch. Such “hybrid foraging” tasks are the subject of this paper. It is also characteristic of a range of real-world tasks beyond the Lego box. Many tasks, from surfing the internet to searching medical images for multiple instances of multiple types of pathologies, can be characterized as “hybrid foraging”. How do the rules of hybrid search and of foraging combine in a hybrid foraging task? Much as in a typical foraging task (search for many possible instances of one possible target), in hybrid foraging the data will show that MVT is a good match to the average patch-switching data. Having many possible target types held in memory gives us another kind of switch to think about. Within the overall patch (i.e., the visual display), we can examine when an observer decides to leave a “run” of selections of one particular type of target for another target type. For example, if you have been selecting alligators, when will you switch to the astronaut or some other target type? Do you switch when the current rate of alligator acquisition drops below the average rate? Interestingly, data from these sub-foraging tasks seem to deviate from MVT. As discussed previously, in hybrid search for one possible instance of many possible targets held in memory, RT is a linear function of the log of memory set size (Wolfe, 2012). In hybrid foraging, $RT \times$ memory set size functions continue to be logarithmic. However, there are separate functions for selections where the current selection is different from the last selection (e.g., astronaut followed by alligator) as compared to the case where the present selection is the same as the previous (e.g., alligator–alligator).

2. Methods

In this hybrid foraging experiment, observers searched for multiple instances of multiple targets. The primary measures of interest were the identity of items collected, the rate of collection, the order in which they were collected, and the point at which observers chose to leave one patch for the next. We will refer to each visual display of items as a “patch” by analogy to the foraging literature and we will refer to each click on a target in a patch as an act of “collection”. In this study, observers held 8, 16, 32, or 64 possible target objects in memory. They then searched for multiple instances of these targets in a succession of patches: large displays of between 60 and 105 items, where 20–30% of all items were targets.

2.1. Stimuli and apparatus

The stimuli were presented on a 24” screen on an iMac, model A1225 (EMC 2211). The experiment was programmed in Matlab 7.10.0 using the Psychtoolbox, version 3.0.9 (Brainard, 1997; Pelli, 1997). Target and distractor items were drawn from 1314 of the photographs of objects used in the picture memory experiments of Brady et al. (2008). Items were up to 75×75 pixels, subtending a maximum of approximately 1.8×1.8 degrees of visual angle at average viewing distance of 24”.

2.2. Procedure

There were four experimental sections, each with a different memory set size, 8, 16, 32, or 64 items. In the first phase of each section, observers memorized the set of target items, viewing each

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