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Spatial memory in foraging games

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ABSTRACT

Foraging and foraging-like processes are found in spatial navigation, memory, visual search, and many other search functions in human cognition and behavior. Foraging is commonly theorized using either random or correlated movements based on Lévy walks, or a series of decisions to remain or leave proximal areas known as "patches". Neither class of model makes use of spatial memory, but search performance may be enhanced when information about searched and unsearched locations is encoded. A video game was developed to test the role of human spatial memory in a canonical foraging task. Analyses of search trajectories from over 2000 human players yielded evidence that foraging movements were inherently clustered, and that clustering was facilitated by spatial memory cues and influenced by memory for spatial locations of targets found. A simple foraging model is presented in which spatial memory is used to integrate aspects of Lévy-based and patch-based foraging theories to perform a kind of area-restricted search, and thereby enhance performance as search unfolds. Using only two free parameters, the model accounts for a variety of findings that individually support competing theories, but together they argue for the integration of spatial memory into theories of foraging.

1. Background

Foraging is a class of general search processes often defined as one or more agents moving through a space to find targets that are relatively finite and have unknown locations. Examples of agents include humans, eyes, or algorithms, and minimization of movement is usually desirable to conserve energy, save time, and minimize risk. Foraging success is commonly defined as the rate at which targets are located per distance or time moved, and researchers have investigated how foraging may be optimized from different theoretical perspectives (Pyke, 1984; Viswanathan, da Luz, Raposo, & Stanley, 2011).

Some researchers theorize foraging as random or correlated walks (Bartumeus, da Luz, Viswanathan, & Catalan, 2005). Such stochastic processes do not require encoding of the environment, and their long-term behaviors may be determined analytically. Random walks with heavy-tailed path length distributions are better than those with normal distributions when targets are sparse and randomly distributed, because the resulting search trajectories cover more search area per unit time (Viswanathan et al., 1999). Studies of animal foraging (Humphries, Weimerskirch, Queiroz, Southall, & Sims, 2012), memory foraging (Rhodes & Turvey, 2007), and visual foraging (Rhodes, Kello, & Kerster, 2014) have all found path length distributions to be heavy-tailed, suggestive of some relationship between foraging and stochastic processes known as *Lévy walks* (Viswanathan et al., 1996). However, few if any search processes are literally Lévy walks because search dynamics are not purely stochastic, and this subtlety has led to much debate and contention about the role of random and correlated walks in theories of foraging (Pyke, 2015).

Other researchers prefer to theorize foraging as an adaptive process that encodes information about the environment as search unfolds (Nathan et al., 2008), in contrast with random and correlated walks. Encoding allows foraging movements to take advantage of environmental structure and regularities (Boyer & Walsh, 2010). For instance, *patch foraging* (Charnov, 1976; Pirolli & Card, 1999) is adaptive in that foraging decisions are based on ongoing estimates of instantaneous rates of target acquisition. The environment is divided into a set of local search regions (i.e., patches), and the fundamental task of search agents is to decide whether to continue foraging in the current patch, or leave to forage another patch. Under certain simplifying assumptions, the optimal decision rule is to stay as long as the current rate of target acquisition is above the long-term expected rate, and to leave when the current rate drops below the expectation (for applications to visual search, see Cain, Vul, Clark, & Mitroff, 2012; Najemnik & Geisler, 2005).

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One simplifying assumption of random and correlated walks, as well as patch foraging, is to set aside the potential influence of spatial organization in the distribution of items being foraged. *Area-restricted search* processes (Hills, 2006; Kareiva & Odell, 1987) are also adaptive and similar to patch foraging, but they are designed to capitalize on spatial clustering that often occurs in search environments. Search is concentrated near locations where targets are found by increasing the degree of turning (or decreasing the lengths of movements) as targets are found, and vice versa as targets are not found. Thus foraging movements remain relatively local when rates of acquisition are high, and become more long-ranging as rates decrease. It has been argued that area-restricted search is an evolutionary innovation (Hills & Dukas, 2012), but the tradeoff relative to patch foraging is that area-restricted search has thus far been defined as heuristic, rather than optimal in terms of maximizing rates of target acquisition.

Patch foraging and area-restricted search are adaptive processes in that they encode information about the environment as search unfolds, but this encoding is fairly minimal. Patch foraging only requires estimates of the current and long-term rates of target acquisition, and area-restricted search only requires an encoding of the current change in rate of target acquisition. Neither spatial memory nor distinct encodings for multiple targets are required. Evidence has been found supporting both patch foraging (Nonacs, 2001; Wolfe, 2003) and area-restricted search (see Hills, Todd, Lazer, Redish, & Couzin, 2015), but it is clear that search processes can be enhanced by spatial memory (Boyer, Crofoot, & Walsh, 2011; Fagan et al., 2013), and there is evidence for the use of spatial memory in primate foraging (Janson, 1998; Janson & Byrne, 2007).

When targets are finite and spatially fixed, spatial memory can help to minimize inefficient revisiting of previously searched locations. A number of visual search studies have investigated whether visual memory actually plays such a role, and while there has been some controversy (Wolfe & Pokorny, 1990) and studies demonstrating a lack of memory (Horowitz & Wolfe, 1998; Peterson, Kramer, Wang, Irwin, & McCarley, 2001), but it is clear that some amount of spatial memory is available to visual search (see Wolfe, 2003). Spatial memory can also be used to discern clustering and other spatial patterns to target locations that may be exploited. Therefore, it stands to reason that search processes will use spatial memory when available and not overly taxing on attentional, perceptual, or cognitive resources. However, it is difficult to test spatial memory in studies of naturalistic foraging, particularly in terms of manipulating factors hypothesized to affect foraging behaviors by virtue of spatial memory processes.

To afford maximum experimental control over foraging conditions, we designed a video game to engage players in an abstraction of naturalistic foraging. Three aspects of the search environment were manipulated to test how spatial memory might guide search movements: Target density, target clustering, and spatial memory cues. Memory can be useful when targets are clustered because foraging should be drawn to clusters as they are located, and higher target densities should provide more information about the locations, shapes, and sizes of clusters. Results are presented and analyzed in terms of performance, path length distributions, spatial clustering, and dependency of search movements on targets found. We find evidence that search trajectories were inherently clustered, as Lévy walks would predict, but also that performance was enhanced by spatial memory—in particular, performance increased with visual landmarks and with increased spatial information in the form of greater target clustering and density. We present a new model of foraging that uses spatial memory to perform efficient search by embodying general properties of inherent clustering akin to Lévy foraging, and area-restricted search akin to patch foraging. We test the model against our search data, and discuss how the model may be adapted to a range of search processes in the behavioral and cognitive sciences.

2. Methods

A foraging video game (http://cogmech.ucmerced.edu/simple) was designed in which players moved a mouse cursor to search. Target locations were always hidden from view, and targets were not replenished once foraged. The foraging space had a maximum resolution of 1280 × 1024 target locations, and the space was scaled to the mouse and screen resolution available on each participant's computer. The cursor appeared as a pointer inside a 15 × 15 square outline that showed the area foraged when clicked. When a click uncovered one or more targets, a chime was sounded once for each target, with a maximum of 9 chimes in rapid succession. To motivate participants, the top 10 high scores were posted and shown to participants at the end of play.

Each participant completed two trials of 300 clicks each, preceded by practice rounds of 15 clicks. Each participant was randomly assigned to play the foraging game with or without visual landmarks. Visual landmarks were created by displaying one of six Hubble space images as a background. These landmarks could serve only as memory aids because target locations were independent of them, as participants were informed. A black background was shown when there were no visual landmarks. One of the two trials per player (chosen at random) included a small movement time cost: Rather than moving instantaneously from one click location to the next, the foraging square moved gradually across the screen at a rate of about 900 pixels per second. Participants had to wait until movement ended before clicking again to forage. Movement cost had no reliable effect on search, so these analyses are not reported or discussed further.

Each player also was randomly assigned to one of three target density conditions, crossed with one of three clustering conditions. There were 100 (sparse), 600 (medium), or 1100 (dense) targets available, and they were placed either randomly, or with one of two different degrees of stochastic clustering. Stochastic clustering was created by a probabilistic, recursive algorithm (Fig. 1) with a parameter that could vary between random placement of targets with no clustering (0.5) and a single cluster of all targets placed in a single random location (0.0). Intermediate values created clusters recursively nested within clusters, randomly located and shaped, with varying degrees of dispersion. Parameter values of 0.1 (most clustered), 0.3 (less clustered), and 0.5 (random) were used for the experiment.

Participants were recruited through Amazon's Mechanical Turk. A job was posted with the title "Space Foraging Game" and the description, "Play a fun game where you travel through space trying to find hidden resources. Takes about 5–10 min." The job was open for 2 days, during which over 2000 players with unique Amazon Turk IDs participated. Participants took 8 min on average to complete the job, and each player was paid 25 cents to complete the game. Nine players were excluded from analyses for failing to perform the task by clicking in the same location every time. Examples of paths produced by participants and background distributions can be viewed in lefthand column of Fig. 2.

Participants were asked to identify the country in which they were currently located: 1519 identified the US, 406 identified India, 58 identified various other countries, and 11 declined to identify. Generalizing from the demographics of participants in previous studies on Mechanical Turk (Ross, Irani, Silberman, Zaldivar, & Tomlinson, 2010), we estimate that the mean age of participants was about 31, of which half were female.