

Foraging in Mind

Peter M. Todd^{1,2}  and Thomas T. Hills³

¹Cognitive Science Program, Indiana University Bloomington; ²Department of Psychological and Brain Sciences, Indiana University Bloomington; and ³Department of Psychology, University of Warwick

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Abstract

People and other animals can search for information inside their heads. Where does this ability come from, and what does it enable cognitive systems to do? In this article, we address the behavioral and cognitive similarities between search in external environments and internal environments (e.g., memory). These require both maplike representations and the means to navigate them, and the latter involves modulation between exploitation and exploration analogous to a foraging process called *area-restricted search*. These findings have implications for understanding a number of cognitive abilities commonly considered to be hallmarks of the human species, such as well-developed executive control and goal-directed cognition, autonoetic consciousness (i.e., self-awareness), deliberation, and free will. Moreover, this research extends our conception of what organisms may share these abilities and how they evolved.

Keywords

search, foraging, memory, executive function, verbal fluency task, cognitive map, episodic future thinking, self-projection

A friend asks you what animals you saw while visiting Tanzania. A lawyer asks about your memories of a criminal incident. A coworker asks what you might do on the coming weekend. And perhaps you ask yourself where you would like to be in 10 years. Do similar cognitive processes underlie these various questions? Some can be answered by *external information search*, such as going back to Tanzania, watching video footage of the crime scene, or looking online for weekend events. But these could also all be addressed by *internal information search*, that is, looking through cognitive representations to recall and reconstruct information from memory, both for retrospective and prospective purposes. In this article, we argue that both of these types of search involve similar underlying cognitive processes that are likely to have common evolutionary origins. Furthermore, being able to search internally, rather than having to move and search around in the external world, has enabled striking evolutionary innovations in cognitive abilities, such as self-projection and self-awareness. Such abilities are commonly seen as unique aspects of the human intellect, but from this evolutionary perspective, they emerge as part of a continuum across species.

key insight is that resource distributions matter. Environments are commonly structured with rewarding resource items near each other (e.g., in patches or clusters). Given this structure, a search strategy that works well to achieve high overall levels of reward is switching between exploiting local resources near where other resources have been found in the past and exploring farther afield when the local resources are depleted. In the ecological literature, this strategy is called *area-restricted search*, and the current evidence suggests that most every organism that moves uses it, from bacteria to people (Hills, 2006; Hills, Kalff, & Wiener, 2013; Pacheco-Cobos et al., 2019).

Area-restricted search can exploit patchy (autocorrelated) structures in the environment by controlling when and where one should look next on the basis of memory of recent experience (Hills, Kalff, & Wiener, 2013; Plank & James, 2008). Consequently, it outperforms other memoryless strategies such as random walks (including Lévy flights) in environments with patchy distributions because the latter do not incorporate information from recent resource encounters. Patchy distributions

Foraging in External Spaces

To understand internal search, it is first important to ask how organisms search in external environments. A

Corresponding Author:

Peter M. Todd, Indiana University Bloomington, Department of Psychological and Brain Sciences, 1101 E. 10th St., Bloomington, IN 47405

E-mail: pmtodd@indiana.edu

are common for useful resources (e.g., conspecifics, food) in the world (Wilke et al., 2018), and people both expect (Wilke & Barrett, 2009) and create (Wilke et al., 2015) such patches.

Moreover, humans create patches not only in physical space (supermarkets full of food, cities full of people) but also in information space: We build autocorrelated structures into our libraries, offices, the World Wide Web, and communities of like-minded individuals, which results in rewarding information items often being found near each other. If you find a bookshelf, or a colleague, or a website that contains useful ideas or data you are seeking, the chances are good that you will find other pieces of related useful information on the same shelf, in the same head, or on a linked web page. Consequently, a mechanism that switches adaptively between local exploitation and global exploration will enable people to effectively engage in *information foraging* in those environments (Pirolli, 2007). As one example, people switch from locally searching a patch of linked websites to globally searching for a new part of the Web when the expected reward from continued search in the first patch falls too low (Pirolli, 2007). Given this patchy structure in many environments, it is not surprising that so many organisms, including humans, use area-restricted search in a variety of contexts.

Perhaps more surprisingly, the neural mechanisms that modulate the transition between exploitative and exploratory search share many common features across animal species (Hills et al., 2015; Todd, Hills, & Robbins, 2012). The cross-species conservation of search-modulating neural architecture provides evidence that this innovation originated in the service of foraging before the invertebrate–vertebrate divergence (~600 million years ago). Furthermore, the presence of a similar architecture underlying goal-directed attention supports a search-based evolutionary account of the origins of executive function and one that may underlie capacities for internal foraging in cognitive representations (Hills, 2006).

Foraging in Internal Spaces

The internal world of our memory reflects properties of the external world. For instance, we encode patchiness in time (Anderson & Schooler, 1991), associations in semantic space (Raaijmakers & Shiffrin, 1981), and maps of physical space (Tolman, 1948) on the basis of our experiences with external information. Therefore, our internal information space is likely to share structural similarity with our external physical space. Specifically, like locations on a spatial map—but in higher dimensions (Jones, Kintsch, & Mewhort, 2006)—information in memory can be near or far from other

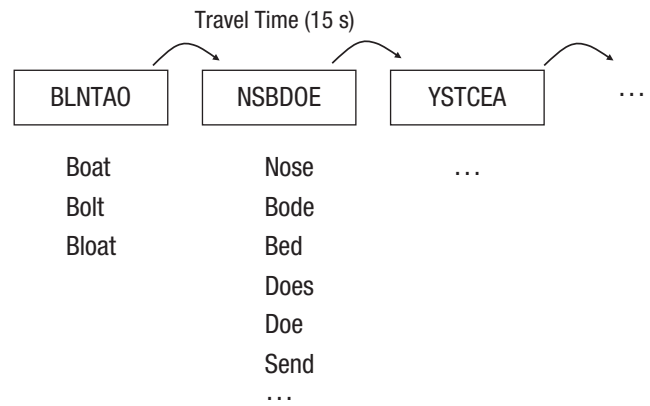


Fig. 1. Internally foraging for words in a memory-based word puzzle (Wilke, Hutchinson, Todd, & Czienskowski, 2009). Participants were presented with a letter set (inside boxes) and tasked with finding words that could be produced from that letter set (example responses are shown below each box). At any point, a participant could give up on the current letter set and move to another one (after a 15-s “travel time”). This process was repeated for an hour, after which participants were paid for the total number of words found across all letter sets. Each letter set corresponds to a resource patch, and participants controlled their exploration/exploitation balance by deciding when to switch between patches. Wilke et al. found that the switching decision was based on the time it took participants to find the most recent word and how long it had been since that word was found (analogous to the time between and since the occurrence of words in external patches in the memory model of Anderson & Schooler, 1991): The more time these took, the more likely participants were to move to a new letter set in which they could expect to start finding words more quickly.

information in memory, and a set of concepts can all be near to each other and far from other sets, making patches. This means that foraging strategies similar to those we use in external environments can also be effective when applied to searching in structured internal environments, such as when solving problems or recalling concepts from memory. Is there evidence for a cognitive equivalent of area-restricted search over internal information landscapes, switching between exploiting clusters of related items and exploring for new clusters when the previous one is depleted?

Some of the earliest work examining this question investigated intermediate environments in which internal and external search constraints are combined. For example, Wilke, Hutchinson, Todd, and Czienskowski (2009) developed a task that bridged problem solving and (internal) memory search using a word puzzle in which participants had to find all the words they could create using sets of random letters (corresponding to externally defined word patches; see Fig. 1). Participants could switch as desired between sets, but doing so would result in a costly delay. In this internal search for anagram solutions and in an analogous external search task for fish in virtual ponds, people used the same type of foraging rule (a variation of area-restricted

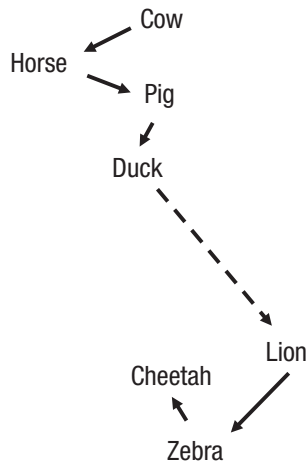


Fig. 2. Internal foraging in the verbal fluency task (Hills, Jones, & Todd, 2012). In the animal fluency task shown here, participants are asked to “name all the animals you can think of.” Behavior follows a pattern of local search within clusters of semantically similar items (solid arrows) and then global search for new clusters, which are typically found by starting with a high-frequency word (dotted arrow). Figure adapted from Hills and Butterfill (2015).

search called an *incremental rule*) to decide when to switch from exploitation to exploration (Hutchinson, Wilke, & Todd, 2008).

To study internal foraging in the absence of external structure, we asked participants in another study to name all the animals they could think of in 3 min (Hills, Jones, & Todd, 2012). In this commonly used verbal fluency task, we found that memory recall was best described as switching back and forth between local search (producing a cluster of semantically similar words) and global search (seeking a new high-frequency word to start a new cluster; see Fig. 2). Individuals switched to new clusters in a manner that matched the central prediction of optimal-foraging theory, the *marginal value theorem* (Charnov, 1976), leaving the current word cluster when their rate of producing words in that cluster fell below their overall mean rate. As in spatial-patch foraging, individuals who followed this area-restricted search strategy—modulating between local exploration and global exploration on the basis of recent resource encounters—had higher overall memory production rates.

Random-walk models of search can mimic some behaviors produced by area-restricted search in particular contexts, including verbal fluency and spatial foraging (Abbott, Austerweil, & Griffiths, 2015; Hills, Kalf, & Wiener, 2013). However, recent research using model comparisons has found evidence for the adaptive transitions predicted by area-restricted search, and not by random walks, between exploratory and exploitative search in memory (Avery & Jones, 2018; Jones, Hills, &

Todd, 2015). Currently, functional MRI studies are underway to compare these models at the level of brain mechanisms.

Do internal and external searches use similar cognitive mechanisms? Evolutionary and empirical evidence suggest that they do, under the common function of goal-directed behavior or executive control (Hills, Todd, & Goldstone, 2010). Measures of executive function correlate with numerous internal and external search tasks (Longstaffe, Hood, & Gilchrist, 2014; Rosen & Engle, 1997). For example, individuals with higher measures of executive control are both better able to identify visual targets in the face of distraction in an external visual search task (Poole & Kane, 2009) and to persist longer in local search in internal search tasks (Hills, Mata, Wilke, & Samanez-Larkin, 2013; Hills & Pachur, 2012). Individual differences may also be preserved across both visual (external) and semantic (internal) search tasks (Van den Driessche, Chevrier, Cleeremans, & Sackur, 2019). Hills, Todd, and Goldstone (2008, 2010) also found evidence for a common underlying process by demonstrating that search strategies could be primed from spatial environments (with resources distributed either diffusely or in clusters) to apply to letter sets (Fig. 3).

Do insights from foraging extend to behavior in still more abstract environments, such as culture? There is reason to expect so. If cultural innovation involves exploration of patchy information environments (Hills et al., 2015), then this may help explain processes of cultural evolution that resemble punctuated equilibrium as stable bouts of exploitation followed by bursts of exploration (Kolodny, Creanza, & Feldman, 2015). People searching for new innovations in a creative space of two-dimensional images showed regular transitions between bouts of exploitation of related designs and exploration for new designs, and they left a cluster to explore more when the novelty of exploited designs in the previous cluster fell (Hart et al., 2018). Search for other people’s cultural creations also appears to move between local exploitation of familiar styles and exploration for new things to try (e.g., for music: Lorince, 2016).

Implications of the Foraging Mind

The prevalence across species of area-restricted search and the shared neuromolecular architectures that underpin it are evolution’s answers to the exploration/exploitation trade-off that must be navigated in a wide variety of external environments (Hills et al., 2015). Ongoing research on the use of these foraging mechanisms to search internally has led to numerous insights regarding the possible evolution of minds such as ours.

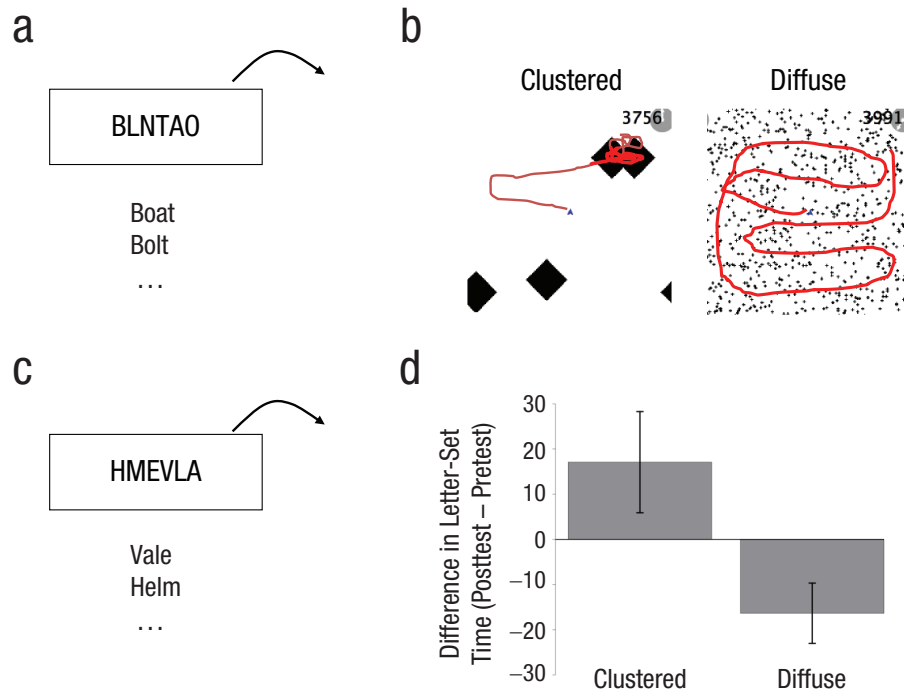


Fig. 3. Evidence for a connection between external and internal search from a priming study incorporating both types of search (Hills, Todd, & Goldstone, 2008, 2010). Participants first played a word puzzle (a; as in Fig. 1) to establish baseline performance. They then played a spatial search game (b) in which they looked for resources hidden in a two-dimensional landscape on a computer screen. For half of the participants, the resources came in clusters (left, shown here in black, although they were invisible to participants until they passed over them). For the rest of the participants, the resources were distributed diffusely (right). Red lines are example mouse trajectories. (Numbers shown are game scores.) Finally (c), participants searched for word-puzzle solutions again. The graph (d) shows the mean difference between the length of time participants searched for letter clusters in the second word-puzzle task and the first, separately for those who saw clustered resources and who saw diffuse resources. Those who searched in the clustered spatial environment stayed significantly longer in word patches afterward, which suggests that increased use of exploitation in the spatial search strategy primed increased exploitation in the internal word search, possibly through a linked dopaminergic mechanism. Portions of this figure adapted from Hills et al. (2008).

These include capacities for deliberation and self-projection, self-awareness, and free will. Researchers continue to debate the existence of many of these faculties in nonhuman animals, but the internal-foraging literature suggests that the differences may be—as Darwin (1871) suggested—“one of degree and not of kind” (p. 105).

Deliberation and self-projection

Deliberation can be defined as the ability to consider alternative courses of action. This can be instantiated as a form of internal foraging and is sometimes associated with the capacity for self-projection, imagining oneself adopting each considered course of action (or mental time travel; see Suddendorf, Addis, & Corballis, 2009). Studies with nonhuman animals have demonstrated phenomenological properties of deliberation. Recordings from hippocampal place cells in rats have

shown preemptive internal foraging of choices of directions to take when navigating a maze, with hippocampal activation being followed by activation in striatal reward centers, allowing the valuing of possible future actions (Pezzulo, van der Meer, Lansink, & Pennartz, 2014; see Redish, 2016, for a review). This is called *episodic future thinking*, and alongside the increasing evidence for episodic memory in nonhuman animals (reviewed by Crystal, 2018), it suggests that internal foraging allows human and nonhuman animals to consider multiple courses of actions before initiating a choice. Perhaps most importantly for establishing humanlike abilities in other species (Suddendorf et al., 2009), internal foraging in nonhuman animals demonstrates the capacity for *generativity*, producing novel goal-directed solutions that the animal has never experienced before (Gupta, van der Meer, Touretzky, & Redish, 2010; Pfeiffer & Foster, 2013).

Self-awareness and auto-noetic consciousness

Internal search requires two closely linked processes (Jones et al., 2015): (a) a representation of the information to be searched along with some instantiation of nearness and farness, what Tolman (1948) referred to as a *cognitive map*, and (b) an attentional search process that controls or guides progress through the internal map. The goal-directed search process is associated with executive function and goal maintenance (Hills et al., 2010) and is synonymous with effortful consciousness, the kind of thinking associated with focused attention, one-thing-at-a-time processing, the ability to produce novelty, and self-report (e.g., Baddeley, 2007).

But internal search may also require another kind of consciousness. Any computational system (animal, robotic, or extraterrestrial) that develops an information representation and the capacity to search over it should also be able to tell the difference between internally imagined “experiences” (generated by episodic future thinking) and real experiences, or the individual will likely suffer from false memories and hallucinations. Hills and Butterfill (2015) argued that the need for this discriminative ability between internal and external foraging provides an evolutionary foothold for self-awareness, similar to what Tulving (1985) described as *auto-noetic consciousness*.

Debates about self-awareness in animals are ongoing and have often relied on mirror self-recognition tasks using the mark test. Researchers have now observed that this task can be solved by primates, dolphins, elephants, chimpanzees, corvids, and more recently, fish. The prediction from internal-foraging research is that self-awareness, whether signaled by self-recognition or not, should be found in animals with the capacity to forage in mind as part of the mechanism that distinguishes between internal and external foraging events and thereby prevents memory errors and associated costly behaviors. (The presence of self-recognition could be an indication that a species engages in internal foraging, but this is not necessarily the case given that self-recognition may have evolved for other purposes.)

Free will and generative self-construction

Free will may at first seem beyond the scope of naturalistic accounts of cognitive capacities. But among compatibilists—people allowing for free will in a deterministic universe—standard requirements for free will include the capacity to “do otherwise” (to take alternative courses of action), to maintain goals, to deliberate over alternatives (internal foraging) in pursuit of said goals, and in the end, to be able to say “I did it” (Dennett, 2015). As our arguments above indicate, internal search and its required processes

satisfy what many philosophers have characterized as these design features of compatibilist free will.

In particular, capacities for self-projection and generation of novelty in episodic future thinking lead to the possibility of generative self-construction (Hills, 2019). This involves a cognitive system, consciously aware of its own internal foraging, that experiences future versions of itself via constructive memory processes that sample from and recombine past experiences, chooses among them on the basis of the expected values associated with those experiences, and then acts to bring the chosen one about. This generative self-construction is a pragmatic and computational conceptualization of free will because it is built from the evolutionarily adaptive components underlying internal foraging mechanisms.

Conclusions

In this article, we have proposed a pathway of search evolving over time from dealing with problems of finding physical resources in space to seeking information resources in the external environment to finding and creating concepts, ideas, and plans internally in the mind. This pathway should apply to any evolved organisms, helping us understand the thought and behavior not only of humans but also of other terrestrial animals and even of organisms that evolved on other worlds (Todd & Miller, 2018). Further research on these common foraging mechanisms could provide insights to aid our interactions with other species, near and far. If these organisms live in environments with clustered resource distributions, then they will likely have evolved capacities for mediating the exploration/exploitation trade-off through some means of cognitive control. And in doing so, they will have gained the foundation for using an internal map and differentiating that use in their imagined plans from their actual movement in the external world—steps on the way to consciousness and free will. Wherever cognition arises, it may march along the same evolutionary pathway that connects everything from the bacteria seeking food in their tiny microcosm to wildebeests grazing on the Serengeti to humans searching for ways to understand the universe.

Recommended Reading

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doi:10.1037/dec0000033. A review of aspects of the exploration/exploitation trade-off in learning and decision-making, arguing for a continuum between the two.

Pirolli, P. (2007). (See References). A thorough review of the research and models of how people organize their information environments and forage through them effectively.

Redish, A. D. (2016). (See References). A thorough review of research on neural mechanisms underlying possible mental search over decision options in rats, connecting to deliberative thinking and mental time travel in humans and providing extensive references.

Todd, P. M., Hills, T. T., & Robbins, T. W. (Eds.) (2012). (See References). An edited book with chapters reviewing research on search in animal behavior, human psychology, neuroscience, and computer science, along with interdisciplinary chapters making connections between fields, all written for nonspecialists.

Transparency

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ORCID iD

Peter M. Todd  <https://orcid.org/0000-0003-0231-513X>

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