

Seeking Inner Knowledge Foraging in Semantic Space

Thomas T. Hills, Nancy B. Lundin, Mahi Luthra, and Peter M. Todd

11.1 Introduction

The first author of this chapter was once invited to give a talk at the Max Planck Institute for Human Development in Berlin, which had recently moved buildings without telling him. Dutifully following the latest online maps, he arrived in an empty building with vacant offices and unswept meeting rooms. A few faded flyers and office name tags confirmed that, in fact, this was a *version* of the correct destination. But it was as if the inhabitants had all left in a hurry. Or possibly Thomas had arrived several decades too late.

Search problems such as the one above typically have *two stages*: the part where you feel close to the resources you are looking for, and the part where you don't. More generally, this is an instance of the *exploration–exploitation trade-off* (Hills et al., 2015). The part where you think you feel close leads to a kind of exploitation of existing knowledge. In this phase, Thomas simply exploited an information trail, both online and in the physical world, because he believed that trail contained the answer to the where-will-I-give-my-talk question. It did not. This led to the second stage, which initially involved investigating different floors in the same building. This only compounded the Phillip K. Dickian nature of the experience (e.g., Dick, 1959). Indeed, here was the room identified as the location of the talk, with dusty desks and nary a soul in sight.¹

The ability to look for things nearby when you expect to find them there, and to look further afield when you do not, is called *area-restricted search*. To a first approximation, roughly all organisms that move do area-restricted search, including bacteria, nematodes, ants, and lost speakers

¹ Having once slept on a train going the wrong way, only to awaken twice as far from his destination as when he started, Thomas didn't put it out of his mind that the problem was of his own creation. It just wasn't obvious to him how he had managed to slip into exactly *this* alternate reality.

(reviewed in Hills, 2006). Bacteria do area-restricted search via their run-and-tumble behavior, which allows them to exploit and “run” up resource gradients – to richer pastures – or to reverse their protein motors and “tumble” – randomly choosing a new direction – when their receptors signal they may be moving down a resource gradient. Nematodes perform a pirouette, touching their nose to their tail, to turn around abruptly when they suddenly find themselves away from food. Ants, even the path-integrating desert ant *Cataglyphis*, engage in area-restricted search, wandering slowly in increasingly wider spirals when they fail to find their home at its expected location.

Lost speakers can tumble and pirouette around buildings. But they can also search inside their heads to generate alternatives to moving through space – like recovering the identity of the person who sent the invitation and phoning them. The notion of embarking on an inner journey, as a surrogate for reality, is often associated with Tolman’s (1948) concept of a *cognitive map*. Tolman, observing rats as they navigated through mazes, often observed in the rats’ behavior what he thought was a kind of deliberation. Given prior experiences with shock in a dark environment, a rat provided with a choice between a dark and a light environment down two alternate arms of a maze would stop at the choice point and apparently consider the possibilities before choosing the light side. Tolman called this behavior *vicarious trial and error learning* and he imagined that the rat was also imagining running through alternative mazes in its head (Tolman & Gleitman, 1949).

More recent work has confirmed Tolman’s suspicions by identifying the neural correlates of these cognitive maps and the internal searches they make possible. Using neuroimaging, we can now “watch” as animals search inside their heads, deliberating over possible alternative choices and investigating the outcomes of those choices in a simulated cognitive environment (Hills, 2019). Much evidence shows that the hippocampus contributes a great deal to the representation and navigation of internal maps, allowing for alternative pathways to be compared and for novel routes to be taken through internal space that have never been encountered before (O’Keefe & Nadel, 1978; Pezzulo, van der Meer, Lansink, & Pennartz, 2014). Curiosity-driven exploration of internal spaces is activated by choice points – as in Tolman’s rat. But exploration is also driven in response to *prediction errors*, which appear to be encoded by both the hippocampus and the anterior cingulate cortex (ACC), which in turn engage the prefrontal cortex (PFC) in search guidance and assessment (Gruber & Ranganath, 2019;

Winstanley et al., 2012). Perhaps even more importantly, the hippocampus encodes information about not only space but also time and conceptual information, suggesting that search processes used to navigate internal space may also govern other forms of internal search, such as episodic and semantic memory search (Constantinescu, O'Reilly, & Behrens, 2016; Hills, 2003; Lundin, 2022; Mack, Love, & Preston, 2016; Morton, Sherrill, & Preston, 2017).

This naturally leads to the question of how internal and external foraging processes might be similar, both in terms of the problems they face – adaptively mediating the exploration–exploitation trade-off – but also in terms of their underlying neuroscience. This is what we explore next.

11.2 Semantic Memory Search as Internal Foraging

The need to search internally extends beyond searching internal representations of external space. In humans and some other species, rich stores of semantic and experiential (autobiographic) information are stored in memory and the structure of these representations has been shown to predict human judgments (e.g., Bhatia, Richie, & Zou, 2019). Though information from these memory representations can “pop” into one’s mind, these representations may also require effortful search, as when coming up with a list of items to pack for a holiday trip. How these search processes work is an area of ongoing study.

One way to investigate these mechanisms is by taking a comparative evolutionary perspective and testing whether particular spatial search strategies seen in a range of species can account for human cognitive search patterns measured in experimental settings. As described, animals ranging from bacteria to lost speakers often employ foraging strategies in which they switch between local search within regions of clustered resources (patch exploitation) and global search between those regions (exploration for new patches). Charnov (1976) described this problem mathematically in what is called the Marginal Value Theorem (MVT). The MVT posits that organisms can maximize their foraging rewards by exploiting local patches until their rate of return drops below the average expectation across all patches, at which point they should transition to exploration for a new patch. Note that the MVT describes a relationship between the structure of resources and the strategic behaviors required to optimally exploit them. The MVT is indifferent to what those resources are or whether or not they lie inside or outside one’s head.

How information is structured in long-term memory therefore makes predictions about the strategies people use to search memory. In particular, we expect transitions between exploration and exploitation that map onto the somewhat categorical structure of memory. Categorical structure in semantic memory corresponds to patchy resource structures in space – categories consisting of multiple items that are “nearby” (similar to) other items, and “more distant” (dissimilar to) items in other categories. And as the evolutionary associations predict, there is evidence suggesting that humans employ patch-like foraging strategies when searching semantic memory (Hills, Jones, & Todd, 2012): people “enter” regions (or patches) of memory that are resource-rich, near items with many close associations, and then transition to exploration when local resources in memory are depleted.

11.2.1 Naturalistic and Experimental Assays of Semantic Foraging

There are numerous naturalistic settings in which foraging-like patterns in semantic memory can be observed and potentially studied. A common example is generating items for a grocery shopping list (Boettcher, Drew, & Wolfe, 2018). A person may begin by adding foods from the produce section to their list, perhaps even by generating further subcategories within that category such as fruits (e.g., apples, bananas) and then vegetables (asparagus, zucchini, mushrooms), next onto grains (spaghetti, rice), and then dairy (milk, yogurt, butter). Others may generate items for their list based on meals of the day, such as breakfast foods, lunch foods, and ingredients for dinner. Still others may organize their list by the regions of the grocery store where they will be shopping. In all these cases, these cognitive processes aid the shopper in identifying and remembering desired food items to purchase. When all the food is prepared, one may need to invite guests to eat it, and the guest list requires searching for and selecting people based on how they are related to one another in an internally represented social network – first immediate family, next friends, then colleagues, etc. (see Hills & Pachur, 2012). Speech during a dinner conversation may also be viewed through a semantic foraging lens, in that people tend to search for a topic to discuss, exploit that area of conversation, and then may decide to switch to new topics when they run out of related things to say. These naturalistic examples showcase how people’s tendencies to search their memories by transitioning between global and local searches may be beneficial for accomplishing tasks or creating positive

social interactions. That being said, studying such search behavior in the wild brings with it the range of challenges of field research.

Research using laboratory-based tasks and internet search behavior has begun to quantify semantic foraging phenomena similar to those observed in these naturalistic settings. A recent study that bridges external and internal search examined curiosity-driven information seeking using Wikipedia (Lydon-Staley et al., 2021). In a relatively unconstrained task, participants were asked to spend 15 minutes a day for 21 days browsing Wikipedia and reading about topics of their choosing. Search behavior was analyzed using graph theoretic metrics, treating pages visited as nodes of a network and the semantic similarity between nodes as weighted edges. People with higher deprivation curiosity (or stronger motivation to fill gaps of knowledge) exhibited greater local search by exploiting relatively tighter networks of concepts and by more frequently returning to previously visited pages. This study and others (Wang & Pleimling, 2017; Fu & Pirolli, 2007) provide insight into individual differences in search behavior in a context highly relevant to today's technology-driven society.

Relatively simple and less time-consuming tasks frequently administered in research and clinical contexts can also provide a window into people's internal cognitive search. In semantic priming paradigms, participants respond to target words (e.g., "dog") after exposure to semantically related (e.g., "cat") and unrelated (e.g., "light") primes, typically exhibiting faster target responses after the semantically related prime (Meyer & Schvaneveldt, 1971). The verbal responses and timing during these tasks provide information about the structure of an individual's semantic associations. However, these tasks are essentially disconnected one-shot productions, with participants being required to quickly direct their attention to the next (usually unrelated) cue after providing a response; consequently, they tell us little about the extended ongoing process of search for multiple items in semantic memory (but see Abbot, Austerweil, & Griffiths, 2015; Jones, Hills, & Todd, 2015).

The category verbal fluency test (Bousfield & Sedgewick, 1944), on the other hand, provides a rich set of data useful for testing semantic foraging mechanisms, as it is an ongoing multiple-item search that involves decisions regarding local and global transitions. In this task, a participant is asked to verbally list as many different items as they can think of from a particular category (e.g., animals, foods, vehicles) within a designated amount of time (e.g., 1–3 minutes). Given the goal of producing as many words as possible, participants may employ a range of strategies to search their semantic memory. The data from this task enables researchers to

operationalize participants' search processes by quantifying "where" they decide to search (semantic similarity between responses), for how long (inter-item response times), and their ultimate success (how many unique words were produced).

11.2.2 *Modeling Foraging in Semantic Space*

Early investigations into category verbal fluency performance reported that participants produced temporally clustered groups of semantically related words (Bousfield & Sedgewick, 1944). Participants were described as exhausting retrieval within a cluster, pausing, and then experiencing an "attainment of insight" in which a new cluster becomes available for retrieval. A later study noted that participants tended to take similar amounts of time to generate each of the items within a semantic cluster, but the gaps between clusters were longer and increased over time, suggesting rapid discovery of the words in one cluster (found in a corresponding "semantic field") interspersed with lengthening exploration for the next semantic field (Gruenewald & Lockhead, 1980). This seminal work informed conceptualizations of verbal fluency performance as a two-component process in which participants alternately "cluster" (produce a set of words within a subcategory) and "switch" (move to a new subcategory when associated words are less readily available in the first subcategory). Troyer and colleagues (1997) introduced a set of norms for particular category fluency tasks (e.g., animals), defining subcategories based on common participant responses (e.g., pets, farm animals, beasts of burden, water animals). While these Troyer norms were a useful first step in quantifying search behavior, their categorical coding scheme does not capture the continuous multidimensional measure of distance (or similarity) between fluency responses that is important for assessing how people may be "foraging" for nearby items in clusters or exploring to find more distant ones. More importantly from a cognitive perspective, it also does not provide a mechanistic explanation of why people decide to switch from one cluster to seek a new one.

Advances in natural language processing have increased researchers' ability to measure and model semantic memory search. Associative semantic models (such as latent semantic analysis [or LSA; Landauer & Dumais, 1997] and Bound Encoding of the Aggregate Language Environment [or BEAGLE; Jones & Mewhort, 2007]) learn associations between words in large text corpora (e.g., Wikipedia) based on direct and indirect word co-occurrence across contexts. They convert word tokens into vector

representations, allowing for the calculation of semantic similarity between two words as the cosine of the angle between their vectors. This fine-grained assessment of similarity between words can be used quantitatively to assess “semantic distance” traveled during search processes, aiding in understanding people’s search strategies in tasks such as verbal fluency.

This approach to measuring semantic distance has been used to test whether participants’ behavior during semantic memory search can be modeled as a form of internal foraging in mind (Hills, Jones, & Todd, 2012; Todd & Hills, 2020). As briefly described earlier, Hills and colleagues found that people produced words in patches, with lower distance (higher similarity) between words within a Troyer-norm-defined subcategory and greater distance (lower similarity) when moving from one patch to the next. People also tended to leave a patch when there were few remaining words to produce nearby in semantic space and when their rate of producing words in the current patch fell below their average rate in the task, following the predictions of the MVT (Charnov, 1976). It remains to be determined whether their patch-leaving decisions are actually based on depletion or on other cues, such as the time since the previous item was found.

The foraging perspective thus provides a productive framework for studying and modeling the strategies people use during semantic search. It also suggests questions to be explored about the neural mechanisms involved and gives new directions for research into individual differences and suboptimal foraging strategies as a potential explanation for impaired verbal fluency performance in clinical populations, as described later.

11.2.3 *Alternative Models to Semantic Foraging*

Semantic foraging as an explanation for verbal fluency behavior is not without its critics, as other researchers have argued that a random walk through semantic networks can sufficiently explain participant word production patterns (Abbott et al., 2015). However, this critique has itself been questioned (Jones, Hills, & Todd, 2015) on the basis of the semantic structure underlying the random walks. Specifically, the random walks in Abbott et al., (2015) took place over semantic networks that were produced from free association data generated by human participants; thus, the representations embedded within the semantic structure were likely generated in a similar fashion to verbal fluency data – that is, via potential foraging search mechanisms. Therefore, there is not yet conclusive evidence as to whether an undirected random walk model explains patchy

semantic search behavior in a way that differs from a strategic search process such as foraging. Nonetheless, what Abbott et al.'s (2015) work does suggest is that a large part of the semantic memory search may reflect an automatic search process similar to reporting the first word that comes to mind in a free association task, possibly leaving more effortful decisions for when and where to initiate the long-distance explorations.

Another related alternative for semantic search processes is the Lévy flight, derived from the ecological literatures. Lévy flights are a type of random walk where directions are chosen at random but path lengths are chosen from a power-law distribution – meaning they are heavy-tailed, such that most path lengths are short, but some are very long (Benhamou, 2007; Viswanathan et al., 1999). Rhodes & Turvey (2007) showed that the time intervals between retrievals in a semantic memory search task were power-law distributed, suggesting the possibility that they may be the outcome of a simple Lévy-like search process. Other research has reported similar relations between semantic memory search and heavy-tailed distributions (Montez et al., 2015; Thompson & Kello, 2014). An observation of heavy-tailed (or power-law) distributions is not sufficient to distinguish between Lévy-like search processes and more adaptive strategies such as area-restricted search. For example, Hills, Kalff, and Wiener (2013) showed that area-restricted search in space – which adaptively reduced path lengths when near clusters of resources – produced path-length distributions that were indistinguishable from Lévy flights. Nonetheless, the question of Lévy processes in memory search is still open, and new experiments are needed to formalize and disentangle Lévy processes from other forms of random walks and area-restricted search.

11.2.4 *Neural Correlates of Internal Foraging*

Investigating patterns of brain activity during search tasks is another way to understand the degree to which internal search aligns with foraging mechanisms. Theories of goal-directed cognition have posited overlap in the neural mechanisms of physical and cognitive foraging behavior, identifying, for example, similar neural circuitry across animals during internal and external search. Specifically, connectivity between the basal ganglia and prefrontal cortex may give rise to adaptive modulation of dopaminergic signaling, which promotes attribution of attentional salience to rewards found in the environment (Hills, 2006; Hills et al., 2015; Todd, Hills, & Robbins, 2012). As mentioned earlier, the hippocampus also serves roles in both external and internal search, with the posterior portion in humans

(dorsal in rodents) critical to navigation in physical space, and the anterior portion (ventral in rodents) theorized to perform similar computations at a more conceptual level, enabling linking of semantic and episodic memory to form higher-level representations (Buzsáki & Moser, 2013; Eichenbaum, 2004; Strange et al., 2014).

Functional magnetic resonance imaging (fMRI) in humans and neuronal firing studies in nonhuman primates have demonstrated robust involvement of the anterior and posterior cingulate cortex in contexts of reward-based decision making (e.g., gambling tasks in humans: Kolling et al., 2012; reward-based motor tasks in monkeys: Shima & Tanji, 1998). Some researchers posit that the anterior cingulate encodes monitoring of foraging risk and reward value (Brown & Alexander, 2017; Kolling et al., 2012), while others suggest this region tracks choice difficulty (Shenhav et al., 2014; Shenhav et al., 2016) and post-decision evaluation of rewards not received (Blanchard & Hayden, 2014). The ventromedial prefrontal cortex has also been frequently implicated as encoding value in reward-based decision-making studies, with debate as to whether this is specific to economic choice between well-defined options (Kolling et al., 2012) or more broadly applicable to foraging contexts of unknown options (Mehta et al., 2019; Shenhav et al., 2016). These regions have also been conceptualized to work together in the context of curiosity-driven information seeking, through encoding and incorporating value information into a cognitive map by the orbitofrontal cortex and monitoring of environmental demands by the anterior cingulate (Wang & Hayden, 2021).

Less work has been done to understand whether neural activation during semantic search resembles foraging-like activity and whether this activity correlates with dopaminergic signaling. Several studies have conducted fMRI while participants perform verbal fluency tasks, revealing a widespread network of activation in frontal, temporal, parietal, insular, cingulate, cerebellar, and subcortical regions (Costafreda et al., 2006; Birn et al., 2010; Gauthier et al., 2009). However, most of these studies have measured brain responses associated with verbal fluency production in general, rather than mapping activation patterns to particular search strategies (e.g., clustering, switching). Preliminary evidence in small samples using brief covert (unspoken) verbal fluency tasks has revealed differential fMRI activation during switching and clustering, with increased switch-related activation in regions such as the inferior frontal gyrus, posterior cerebellum, and posterior parietal cortex, among others (Gurd et al., 2002; Hirshorn & Thompson-Schill, 2006). In a verbal fluency fMRI study with 3 minute periods of overt word generation, we more directly tested

whether neural activation reflects patterns that align more strongly with foraging or random walk theories, in part by examining whether activation in particular regions differs in magnitude and localization during local and global semantic search and increases in a ramp-like fashion over a patch until reaching a switch (Lundin, 2022). In this study, both the anterior hippocampus and posterior cerebellum showed increasing activity leading up to the decision to switch, suggesting neural processes related to a strategic foraging process (e.g., switching based on monitoring search effort) as opposed to an undirected random walk.

11.2.5 Individual Differences and Disruptions in Semantic Search

Quantifying semantic search in terms of specific component processes such as exploration and exploitation opens up novel opportunities for investigations of individual differences in cognitive functioning. This can involve individual differences in strategy and differences associated with age (Hills, Mata, Wilke, & Samanez-Larkin, 2013), cognitive impairment, and/or psychopathology (Taler, Johns, Sheppard, & Jones, 2015). For example, while associative search accurately describes verbal fluency search behavior in some participants, other participants' response production may be better described by a categorical search process (Hills et al., 2012; Hills et al., 2015). In other words, some people may search their semantic memory by making decisions as to whether there are items readily available similar to the last item retrieved, whereas others may make decisions as to whether there are available items remaining within that subcategory (e.g., pets, farm animals). In conjunction with analyzing response production, directly asking participants about their search strategies could provide additional insight into individual differences in semantic search.

Studying semantic search within clinical populations could aid in diagnostic characterization. Impairments in verbal fluency production have been reported in individuals with neurological conditions such as dementia (Henry et al., 2004) and frontal and temporal lobe lesions (Troyer et al., 1998), as well as psychiatric illnesses such as schizophrenia (Bokat & Goldberg, 2003) and depression (Henry & Crawford, 2005). While individuals across these groups tend to generate fewer words in verbal fluency tests, different specific cognitive functions are likely impaired between groups. For example, particular types of dementia may be associated with a degradation of semantic representations in long-term memory (Laisney et al., 2009), whereas schizophrenia may be associated with disrupted executive and/or processing speed functions which impair fluid

retrieval of semantically related words (Joyce et al., 1996; Lundin et al., 2020; van Beilen et al., 2004; Taler et al., 2015). More research is needed to disentangle the specific mechanisms of impaired semantic search in these heterogeneous clinical populations.

There is an additional challenge relevant to studying individual differences in search strategies. Because observable search responses result from an interaction between one's semantic representations and the strategies used to retrieve them (Jones et al., 2015), researchers need to evaluate both before assuming differences are caused exclusively by one or the other (for a more detailed discussion, see Hills & Kenett, 2021). Individuals may have different categorical (patch) knowledge and structures in semantic memory, as in the grocery shopping list example earlier, and the expert category knowledge of bird watchers or dog breeders, which could erroneously make their navigation of semantic space appear to operate differently from that of other people.

11.3 How Memory Search Changes the Internal Search Environment

The previous section showed how search strategies may be adapted to the distribution of resources (e.g., local-to-global search fitting patchy semantic memories). Much of the research on this topic investigates search behavior assuming a static distribution of resources. However, this assumption often does not hold for real-world systems – in most situations, distributions of resources are very much influenced by the search behavior of resource consumers – that is, search strategies and resource distributions mutually influence one another. In the current section, we consider this dynamical interaction between search and structure. We begin by describing the influence of memory search on memory networks – and hence, on subsequent searches. Based on this, we then consider possible explanations specifically for the patchy structure of semantic memory.

11.3.1 Semantic Search Influences Semantic Network Structure

We first illustrate the influence of search strategies on resource distributions using ecological examples – which, as the preceding sections argued, should then help us develop hypotheses that generalize from physical ecological environments to abstract mental environments. As stated earlier, ecological resources often come distributed in patches (Levin, 1992). Many ecologists indicate that such patchiness is a consequence of search

processes themselves. For instance, phytoplankton are patchily distributed at multiple scales of measurement, and Levin (1992) suggests that this patchiness arises not only from physical processes such as drift diffusion or habitat events such as water currents, but also through the search behavior of plankton-consuming species such as krill. Using agent-based modeling simulations, Luthra, Izquierdo, and Todd (2020) studied mutual interactions of environmental patchiness and simple search strategies (exploration vs. exploitation with varying range of perception) that evolved among simulated plants and foragers. They found that patchiness emerged through the behavioral impact of searching consumers (foragers) on the spatial distribution of resources (plants) in the environment, and the patchiness in turn led to the evolution of more effective forager search strategies, creating an ongoing dynamical interaction between the two. Using similar methods, Luthra and Todd (2021) studied mutual interactions between social rather than individual search (i.e., consumers used information about the whereabouts of other consumers to locate resources) and resource patchiness, finding that each increased the level of the other up to a particular threshold.

Similar ideas of bidirectional interactions between search strategies and resource distributions can be applied to memory search. Unlike ecological spaces, memory spaces are not usually conceptualized as simple two- or three-dimensional Euclidean environments, but rather as higher-dimensional spaces or networks. Here, distance is the inverse of the strength of connections between concepts: the stronger a connection between two semantic concepts, the easier and quicker it is to traverse from one to the other (as with locations that lie physically close to one another). Hence, resource distributions in semantic memory can be quantified based on strength of memory connections (Rips, Shoben, & Smith, 1973).

Several studies indicate that semantic resources, like ecological resources, have a patchy distributional structure. Researchers have used tools from graph theory to analyze properties of human semantic networks derived from word association tasks, where participants generate words associated with presented cue words (Dubossarsky, De Deyne, & Hills, 2017; Morais, Olsson, & Schooler, 2013; Steyvers & Tenenbaum, 2005). Investigations find that these semantic networks have a high clustering coefficient – that is, groups of semantic concepts tend to be tightly knit, with a large density of within-group ties. Similar measures of aggregation are often used to estimate patchiness of ecological resources (Lloyd, 1967).

How are such structures in memory created and changed over time? That is, what processes influence the formation and ongoing strength of connections between concepts in memory? Some of the earliest research on long-term memory indicated that searching and retrieving semantic memories alters their structure (e.g., Jones, 1923). Most research has demonstrated the power of retrieval to improve recall – this effect has been found with nonsense words (Gates, 1917), pictures (Wheeler & Roediger, 1992), visual-auditory stimuli pairs (Nyberg et al., 2000), and word pairs (Pyc & Rawson, 2009). Other studies indicate that memory search can alter connections *between* concepts, strengthening those between arbitrary items that are activated simultaneously. For instance, in one study (Hupbach et al., 2007) participants learned two lists of words across two days. Researchers found that reminding participants of the first learning experience prior to studying the second list led to more confusion between the two lists than not recalling the first learning experience, indicating that memory retrieval strengthened the connections between the two arbitrary lists. Further, there is ample evidence to suggest that retrieval not only strengthens connections between activated concepts, but also weakens those between competing concepts. Across several studies on retrieval-induced failure, Anderson, Bjork, and Bjork (1994) found that connections between word pairs (e.g., *fruit–apple*) are weakened after retrieval practice with competing word pairs (e.g., making participants practice completion of *fruit–pe__* for *fruit–pear* weakens the *fruit–apple* connection). Thus, searching for and retrieving information can both strengthen and diminish semantic memory connections, actively influencing the structure of items distributed in memory, just as distributions of ecological resources are influenced by search and consumption.

To complement such behavioral studies, researchers have obtained neurological evidence of retrieval-based strengthening of memory connections. In experiments with rats, researchers found that proteins suspected to be involved in memory formation are synthesized in neurons not only during memory encoding, but also during retrieval, in a process of memory reconsolidation (Nader, Schafe, & Le Doux, 2000). Other studies have found that retrieval of memories involves brain structures similar to those used in encoding new ones (Gelbard-Sagiv et al., 2008; Chadwick et al., 2010). In support of Anderson, Bjork, and Bjork's (1994) classic studies of retrieval-induced forgetting, Wimber et al. (2015) reported that memory retrieval leads to active suppression of cortical patterns of competing memories, potentially produced by engaging regions of the prefrontal cortex. These studies imply that memory search and retrieval do not simply

entail a passive read-out of information from the store of memory, but rather, similar to encoding, also involve reactivation of memory traces, suppression of competing ones, and thus overall alteration of connections.

As we interact with the external world, we are continually searching for, reactivating, and thereby altering stored concepts. For instance, when using a tool, we must search for and retrieve semantic information related to it. Further, not all stored information is needed at all times, hence memory structures need to be tuned to provide us with appropriate, context-relevant information when it is useful (Anderson & Schooler, 1991). As an important instance of this, concepts frequently encountered together in the real world and consequently frequently retrieved together will also have stronger connections between them in memory which facilitate their joint retrieval. This is demonstrated by extensive priming research: presentation of semantic concepts (e.g., *sleep*) typically leads to increased accessibility of contextually associated concepts (e.g., *pillow*) that are frequently encountered and recalled together in everyday life. Various models have been developed to account for such priming effects, including spreading activation (Anderson & Pirolli, 1984) and prime/target compound cue combination (Ratcliff & McKoon, 1988). Using language also requires repeated searching, retrieval, and recombination of concepts, again changing their internal structural configuration over time. Even more, our constant communication with others makes our semantic structures susceptible to the memory search performed by others which results in the concepts they communicate to us. Such effects are particularly important as children interact with adults to learn language. For instance, bilingual children's poorer performance on verbal fluency tasks and greater susceptibility to tip-of-the-tongue phenomena may reflect retrieval difficulties produced by unintended interference from the competing language (Sandoval et al., 2017).

Memory connections are therefore examples of stigmergic structures. Stigmergy is a mechanism of indirect coordination through which prior events perpetuate occurrence of future events. A popular example of stigmergy is that of ants producing pheromone trails to assist future ants in locating food. Researchers frequently distinguish between individualistic stigmergy (wherein the actions of a single agent perpetuate its own future actions) and collective stigmergy (wherein multiple agents indirectly coordinate to produce future events; Heylighen, 2016). Many stigmergic events can be imagined as a combination of both. For instance, pheromone trails not only enable a single ant to find food locations again, but also foster cooperation between ants for collectively finding food locations.

Memory traces are similar: connections left behind by previous activations enable the same person to retrieve the information again more efficiently, and when the connections of earlier activations are recorded externally as physical markers (e.g., in the form of verbal and written communication), they can influence and coordinate the behavior of others.

11.3.2 *Explanations for Patchiness in Semantic Memory*

So far, we have provided evidence to suggest that searching through semantic memory influences its network structure. But what is it about the way we search that specifically produces patchiness in semantic memories? We mentioned earlier that analyses of semantic networks indicate that they have high clustering coefficients – that is, they are patchy (Morais, Olsson, & Schooler, 2013; Steyvers & Tenenbaum, 2005). These same studies also find that semantic memories have a low average path length between two random nodes in the network. That is, it is possible to connect any two seemingly unrelated semantic concepts by traversing only a small number of connections. For instance, although *sleep* and *duck* might seem like distant concepts, it is possible to connect the two by following the path *sleep-pillow-feather-duck*. In graph theory, networks featuring these two features (patchiness and small path length) are known as small-world networks.

How do small-world structures in semantic memory develop? We have argued that connections in memory develop due to activations produced through encountering semantic concepts in the real world. This suggests that semantic structures come to resemble existing structures in the world, and so to the extent that the contents of the world have small-world structure, so too will some of the contents of mind. In fact, much recent research has focused on the discovery of small-world architectures across real-world network systems. Researchers find evidence for small-world features in human-constructed domains including language (Ferrer i Cancho & Solé, 2001), social groups (Davidsen et al., 2002), transport systems (Sen et al., 2003), and the world-wide web (Adamic, 1999), as well as in other naturally occurring systems such as pollination networks (Olesen et al., 2006) and food webs (Montoya & Solé, 2002). Hence, potentially, some internal semantic networks could reflect small-world structures of the external world. Furthermore, dynamical interactions between internal semantic structures and external social structures (e.g., language, social media) serve to reinforce small-world features in both – that is, small-world structures in semantic memory get reflected in social

systems (e.g., distribution of words in language or connections on social media), which in turn reinforce the small-worldness of semantic memory.

Small-world patchy structures may thus arise internally in semantic memory through search processes that make memory reflect external structures. But these patchy semantic structures could also emerge through internal adaptive processes, independent of external structure, because of their high efficiency for information search and transmission. Since small-world networks have a high level of clustering, they foster efficient local interactions, and because of their low path distance, they also promote global search (Latora & Marchiori, 2001). These adaptive benefits perhaps encourage the emergence and selection of small-worldness in search networks, including semantic ones. Supporting this hypothesis, agent-based simulations by Williams (2019) showed that optimizing simple neural networks to perform lifelike search behaviors such as finding food and mates using genetic algorithms and Hebbian learning leads them to develop small-world architectures. Hence, features of small-worldness – high patchiness and low path length – are likely to also emerge in semantic memory, created by and optimized for the act of memory search.

11.4 Conclusions

External and internal searches share similar strategies. They also operate on spaces that share similar structure. More speculatively, the structure of inner space (like that of the external world) may be partly constructed by the mechanisms we use to search it. Together, this suggests that the similarities between inner and outer space are not only a function of the inner world reflecting the outer world. They are also a product of imposing search processes originally evolved for navigating the external spatial world onto our internal world. The inner world is clearly not a perfect reflection of the outer world; importantly, many things come out of our heads that do not (yet) exist outside, forming the basis of innovation (Hills, 2019). Consequently, the search processes we describe here for space and memory apply to problem solving and exploration more generally – domains where areas of the cognitive map are uncharted until we start looking. In that way, our internal and external search also governs what, just beyond the horizons of the known, we are likely to find.

References

- Abbott, J. T., Austerweil, J. L., & Griffiths, T. L. (2015). Random walks on semantic networks can resemble optimal foraging. *Psychological Review*, 122(3), 558–569.

- Adamic, L. A. (1999). The small world web. *International Conference on Theory and Practice of Digital Libraries*, 1696, 443–452.
- Anderson, M. C., Bjork, R. A., & Bjork, E. (1994). Remembering can cause forgetting: Retrieval dynamics in long-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 20(5), 1063–1087.
- Anderson, J. R., & Pirolli, P. L. (1984). Spread of activation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 10(4), 791–798.
- Anderson, J. R., & Schooler, L. J. (1991). Reflections of the environment in memory. *Psychological Science*, 2(6), 396–408.
- Benhamou, S. (2007). How many animals really do the Lévy walk? *Ecology*, 88(8), 1962–1969.
- Bhatia, S., Richie, R., & Zou, W. (2019). Distributed semantic representations for modeling human judgment. *Current Opinion in Behavioral Sciences*, 29, 31–36.
- Birn, R. M., Kenworthy, L., Case, L., Caravella, R., Jones, T. B., Bandettini, P. A., & Martin, A. (2010). Neural systems supporting lexical search guided by letter and semantic category cues: A self-paced overt response fMRI study of verbal fluency. *Neuroimage*, 49(1), 1099–1107.
- Blanchard, T. C., & Hayden, B. Y. (2014). Neurons in dorsal anterior cingulate cortex signal postdecisional variables in a foraging task. *Journal of Neuroscience*, 34(2), 646–655.
- Boettcher, S. E., Drew, T., & Wolfe, J. M. (2018). Lost in the supermarket: Quantifying the cost of partitioning memory sets in hybrid search. *Memory & Cognition*, 46(1), 43–57.
- Bokat, C. E., & Goldberg, T. E. (2003). Letter and category fluency in schizophrenic patients: A meta-analysis. *Schizophrenia Research*, 64(1), 73–78.
- Bousfield, W. A., & Sedgewick, C. H. W. (1944). An analysis of sequences of restricted associative responses. *The Journal of General Psychology*, 30(2), 149–165.
- Brown, J. W., & Alexander, W. H. (2017). Foraging value, risk avoidance, and multiple control signals: How the anterior cingulate cortex controls value-based decision-making. *Journal of Cognitive Neuroscience*, 29(10), 1656–1673.
- Buzsáki, G., & Moser, E. I. (2013). Memory, navigation and theta rhythm in the hippocampal-entorhinal system. *Nature Neuroscience*, 16(2), 130–138.
- Chadwick, M. J., Hassabis, D., Weiskopf, N., & Maguire, E. A. (2010). Decoding individual episodic memory traces in the human hippocampus. *Current Biology*, 20(6), 544–547.
- Charnov, E. L. (1976). Optimal foraging, the marginal value theorem. *Theoretical Population Biology*, 9(2), 129–136.
- Constantinescu, A. O., O'Reilly, J. X., & Behrens, T. E. (2016). Organizing conceptual knowledge in humans with a gridlike code. *Science*, 352(6292), 1464–1468.
- Costafreda, S. G., Fu, C. H., Lee, L., Everitt, B., Brammer, M. J., & David, A. S. (2006). A systematic review and quantitative appraisal of fMRI studies of verbal fluency: Role of the left inferior frontal gyrus. *Human Brain Mapping*, 27(10), 799–810.

- Davidson, J., Ebel, H., & Bornholdt, S. (2002). Emergence of a small world from local interactions: Modeling acquaintance networks. *Physical Review Letters*, 88 (12), 128701.
- Dick, P. K. (1959). *Time out of joint*. J. B. Lippencott & Co.
- Dubossarsky, H., De Deyne, S., & Hills, T. (2017). Quantifying the structure of free association networks across the lifespan. *Developmental Psychology*, 53, 1560–1570.
- Eichenbaum, H. (2004). Hippocampus: Cognitive processes and neural representations that underlie declarative memory. *Neuron*, 44(1), 109–120.
- Ferrer i Cancho, R., & Solé, R. V. (2001). The small world of human language. *Proceedings of The Royal Society B*, 268, 2261–2265.
- Fu, W. T., & Piroli, P. (2007). SNIF-ACT: A cognitive model of user navigation on the World Wide Web. *Human-Computer Interaction*, 22(4), 355–412.
- Gates, A. I. (1917). Recitation as a factor in memorizing. *Archives of Psychology*, 6, 40.
- Gauthier, C. T., Duyme, M., Zanca, M., & Capron, C. (2009). Sex and performance level effects on brain activation during a verbal fluency task: A functional magnetic resonance imaging study. *Cortex*, 45(2), 164–176.
- Gelbard-Sagiv, H., Mukamel, R., Harel, M., Malach, R., & Fried, I. (2008). Supporting online material internally generated reactivation of single neurons in human hippocampus during free recall. *Science Reports*, 322, 96–101.
- Gruber, M. J., & Ranganath, C. (2019). How curiosity enhances hippocampus-dependent memory: The prediction, appraisal, curiosity, and exploration (PACE) framework. *Trends in Cognitive Sciences*, 23(12), 1014–1025.
- Gruenewald, P. J., & Lockhead, G. R. (1980). The free recall of category examples. *Journal of Experimental Psychology: Human Learning and Memory*, 6(3), 225–240.
- Gurd, J. M., Amunts, K., Weiss, P. H., Zafiris, O., Zilles, K., Marshall, J. C., & Fink, G. R. (2002). Posterior parietal cortex is implicated in continuous switching between verbal fluency tasks: An fMRI study with clinical implications. *Brain*, 125(5), 1024–1038.
- Henry, J. D., & Crawford, J. R. (2005). A meta-analytic review of verbal fluency deficits in depression. *Journal of Clinical and Experimental Neuropsychology*, 27(1), 78–101.
- Henry, J. D., Crawford, J. R., & Phillips, L. H. (2004). Verbal fluency performance in dementia of the Alzheimer's type: A meta-analysis. *Neuropsychologia*, 42(9), 1212–1222.
- Heylighen, F. (2016). Stigmergy as a universal coordination mechanism II: Varieties and evolution. *Cognitive Systems Research*, 38, 50–59.
- Hills, T. (2003). Towards a unified theory of animal event timing. In W. H. Meck (Ed.), *Functional and neural mechanisms of interval timing* (pp. 77–111). New York: CRC Press.
- Hills, T. T. (2006). Animal foraging and the evolution of goal-directed cognition. *Cognitive Science*, 30(1), 3–41.

- Hills, T. T. (2019). Neurocognitive free will. *Proceedings of the Royal Society B*, 286 (1908), 20190510.
- Hills, T. T., Jones, M. N., & Todd, P. M. (2012). Optimal foraging in semantic memory. *Psychological Review*, 119(2), 431–440.
- Hills, T. T., Kalff, C., & Wiener, J. M. (2013). Adaptive Lévy processes and area-restricted search in human foraging. *PLoS One*, 8(4), e60488.
- Hills, T. T., & Kenett, Y. (2021). Is the mind a network? Maps, vehicles, and skyhooks in cognitive network science. *Topics in Cognitive Science*. <https://onlinelibrary.wiley.com/doi/abs/10.1111/tops.12570>
- Hills, T. T., Mata, R., Wilke, A., & Samanez-Larkin, G. R. (2013). Mechanisms of age-related decline in memory search across the adult life span. *Developmental Psychology*, 49(12), 2396.
- Hills, T. T., & Pachur, T. (2012). Dynamic search and working memory in social recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 38(1), 218.
- Hills, T. T., Todd, P. M., Lazer, D., Redish, A. D., Couzin, I. D., & Cognitive Search Research Group (2015). Exploration versus exploitation in space, mind, and society. *Trends in Cognitive Science*, 19(1), 46–54. doi:10.1016/j.tics.2014.10.004
- Hirshorn, E. A., & Thompson-Schill, S. L. (2006). Role of the left inferior frontal gyrus in covert word retrieval: Neural correlates of switching during verbal fluency. *Neuropsychologia*, 44(12), 2547–2557.
- Hupbach, A., Gomez, R., Hardt, O., & Nadel, L. (2007). Reconsolidation of episodic memories: A subtle reminder triggers integration of new information. *Learning & Memory*, 14, 47–53.
- Jones, H. E. (1923). The effects of examination on the performance of learning. *Archives of Psychology*, 10, 1–70.
- Jones, M. N., Hills, T. T., & Todd, P. M. (2015). Hidden processes in structural representations: A reply to Abbott, Austerweil, and Griffiths (2015). *Psychological Review*, 122(3), 570–574.
- Jones, M. N., & Mewhort, D. J. (2007). Representing word meaning and order information in a composite holographic lexicon. *Psychological Review*, 114(1), 1–37.
- Joyce, E. M., Collinson, S. L., & Crichton, P. (1996). Verbal fluency in schizophrenia: Relationship with executive function, semantic memory and clinical alogia. *Psychological Medicine*, 26(1), 39–49.
- Kolling, N., Behrens, T. E., Mars, R. B., & Rushworth, M. F. (2012). Neural mechanisms of foraging. *Science*, 336(6077), 95–98.
- Laisney, M., Matuszewski, V., Mézenge, F., Belliard, S., de la Sayette, V., Eustache, F., & Desgranges, B. (2009). The underlying mechanisms of verbal fluency deficit in frontotemporal dementia and semantic dementia. *Journal of Neurology*, 256(7), 1083–1094.
- Landauer, T. K., & Dumais, S. T. (1997). A solution to Plato's problem: The latent semantic analysis theory of acquisition, induction, and representation of knowledge. *Psychological Review*, 104(2), 211–240.

- Latora, V., & Marchiori, M. (2001). Efficient behavior of small-world networks. *Physical Review Letters*, 87(19), 198701.
- Levin, S. A. (1992). The problem of pattern and scale in ecology. *Ecology*, 73(6), 1943–1967.
- Lloyd, M. (1967). Mean crowding. *Journal of Animal Ecology*, 36(1), 1–30.
- Lundin, N. B. (2022). Disorganized speech in psychosis: Computational and neural markers of semantic foraging and discourse cohesion. Unpublished doctoral dissertation. Indiana University Bloomington.
- Lundin, N. B., Todd, P. M., Jones, M. N., Avery, J. E., O'Donnell, B. F., & Hetrick, W. P. (2020). Semantic search in psychosis: Modeling local exploitation and global exploration. *Schizophrenia Bulletin Open*, 1(1), sgaa011.
- Luthra, M., Izquierdo, E. J., & Todd, P. M. (2020). Cognition evolves with the emergence of environmental patchiness. In J. Bongard, J. Lovato, L. Herbert-Dufresne, R. Dasari, & L. Soros (Eds.), *Proceedings of the Artificial Life Conference 2020* (pp. 450–458). MIT Press. <https://direct.mit.edu/isal/proceedings/isal2020/450/98395>
- Luthra, M. & Todd, P. M. (2021). Social search evolves with the emergence of clustered environments. In J. Čejková, S. Holler, L. Soros, & O. Witkowski (Eds.), *Proceedings of the Artificial Life Conference 2021* (pp. 182–190). MIT Press.
- Lydon-Staley, D. M., Zhou, D., Blevins, A. S., Zurn, P., & Bassett, D. S. (2021). Hunters, busybodies and the knowledge network building associated with deprivation curiosity. *Nature Human Behaviour*, 5(3), 327–336.
- O'Keefe, J., & Nadel, L. (1978). *The hippocampus as a cognitive map*. Oxford University Press.
- Mack, M. L., Love, B. C., & Preston, A. R. (2016). Dynamic updating of hippocampal object representations reflects new conceptual knowledge. *Proceedings of the National Academy of Sciences*, 113(46), 13203–13208.
- Mehta, P. S., Tu, J. C., LoConte, G. A., Pesce, M. C., & Hayden, B. Y. (2019). Ventromedial prefrontal cortex tracks multiple environmental variables during search. *Journal of Neuroscience*, 39(27), 5336–5350.
- Meyer, D. E., & Schvaneveldt, R. W. (1971). Facilitation in recognizing pairs of words: Evidence of a dependence between retrieval operations. *Journal of Experimental Psychology*, 90(2), 227.
- Montez, P., Thompson, G., & Kello, C. T. (2015). The role of semantic clustering in optimal memory foraging. *Cognitive Science*, 39(8), 1925–1939.
- Montoya, J. M., & Solé, R. V. (2002). Small world patterns in food webs. *Journal of Theoretical Biology*, 214(3), 405–412.
- Morais, A. S., Olsson, H., & Schooler, L. J. (2013). Mapping the structure of semantic memory. *Cognitive Science*, 37(1), 125–145.
- Morton, N. W., Sherrill, K. R., & Preston, A. R. (2017). Memory integration constructs maps of space, time, and concepts. *Current Opinion in Behavioral Sciences*, 17, 161–168.

- Nader, K., Schafe, G. E., & Le Doux, J. E. (2000). Fear memories require protein synthesis in the amygdala for reconsolidation after retrieval. *Nature*, 406(6797), 722–726.
- Nyberg, L., Habib, R., McIntosh, A. R., & Tulving, E. (2000). Reactivation of encoding-related brain activity during memory retrieval. *Proceedings of the National Academy of Sciences*, 97(20), 11120–11124.
- Olesen, J. M., Bascompte, J., Dupont, Y. L., & Jordano, P. (2006). The smallest of all worlds: Pollination networks. *Journal of Theoretical Biology*, 240(2), 270–276.
- Pezzulo, G., van der Meer, M.A., Lansink, C.S., & Pennartz, C.M. (2014). Internally generated sequences in learning and executing goal-directed behavior. *Trends in Cognitive Sciences*, 18, 647–657. doi:10.1016/j.tics.2014.06.011
- Pyc, M. A., & Rawson, K. A. (2009). Testing the retrieval effort hypothesis: Does greater difficulty correctly recalling information lead to higher levels of memory? *Journal of Memory and Language*, 60(4), 437–447.
- Ratcliff, R., & McKoon, G. (1988). A retrieval theory of priming in memory. *Psychological Review*, 95(3), 385–408.
- Rhodes, T., & Turvey, M. T. (2007). Human memory retrieval as Lévy foraging. *Physica A: Statistical Mechanics and its Applications*, 385(1), 255–260.
- Rips, L. J., Shoben, E. J., & Smith, E. E. (1973). Semantic distance and the verification of semantic relations. *Journal of Verbal Learning and Verbal Behavior*, 12(1), 1–20.
- Sandoval, T. C., Gollan, T. H., Ferreira, V. S., & Salmon, D. P. (2017). What causes the bilingual disadvantage in verbal fluency? The dual-task analogy. *Bilingualism: Language and Cognition*, 13(2), 231–252.
- Sen, P., Dasgupta, S., Chatterjee, A., Sreeram, P. A., Mukherjee, G., & Manna, S. S. (2003). Small-world properties of the Indian railway network. *Physical Review*, 67, 036106.
- Shenhav, A., Straccia, M. A., Botvinick, M. M., & Cohen, J. D. (2016). Dorsal anterior cingulate and ventromedial prefrontal cortex have inverse roles in both foraging and economic choice. *Cognitive, Affective, & Behavioral Neuroscience*, 16(6), 1127–1139.
- Shenhav, A., Straccia, M. A., Cohen, J. D., & Botvinick, M. M. (2014). Anterior cingulate engagement in a foraging context reflects choice difficulty, not foraging value. *Nature Neuroscience*, 17(9), 1249–1254.
- Shima, K., & Tanji, J. (1998). Role for cingulate motor area cells in voluntary movement selection based on reward. *Science*, 282(5392), 1335–1338.
- Steyvers, M., & Tenenbaum, J. B. (2005). The large-scale structure of semantic networks: Statistical analyses and a model of semantic growth. *Cognitive Science*, 29(1), 41–78.
- Strange, B. A., Witter, M. P., Lein, E. S., & Moser, E. I. (2014). Functional organization of the hippocampal longitudinal axis. *Nature Reviews Neuroscience*, 15(10), 655–669.

- Taler, V., Johns, B., Sheppard, C., & Jones, M. (2015, December). Determining the linguistic information sources underlying verbal fluency performance across aging and cognitive impairment. *Canadian Journal of Experimental Psychology-Revue Canadienne De Psychologie Experimentale*, 69(4), 369–369.
- Thompson, G. W., & Kello, C. (2014). Walking across Wikipedia: A scale-free network model of semantic memory retrieval. *Frontiers in Psychology*, 5, 86.
- Todd, P. M., & Hills, T.T. (2020). Foraging in mind. *Current Directions in Psychological Science*, 20(3), 309–315. <https://doi.org/10.1177/0963721420915861>
- Todd, P. M., Hills, T. T., & Robbins, T. W. (Eds.). (2012). *Cognitive search: Evolution, algorithms, and the brain*. MIT Press.
- Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review*, 55, 189–208.
- Tolman, E. C., & Gleitman, H. (1949). Studies in learning and motivation: I. Equal reinforcements in both end-boxes, followed by shock in one end-box. *Journal of Experimental Psychology*, 39, 810–819.
- Troyer, A. K., Moscovitch, M., & Winocur, G. (1997). Clustering and switching as two components of verbal fluency: Evidence from younger and older healthy adults. *Neuropsychology*, 11(1), 138–146.
- Troyer, A. K., Moscovitch, M., Winocur, G., Alexander, M. P., & Stuss, D. O. N. (1998). Clustering and switching on verbal fluency: The effects of focal frontal- and temporal-lobe lesions. *Neuropsychologia*, 36(6), 499–504.
- van Beilen, M., Pijnenborg, M., van Zomeren, E. H., van den Bosch, R. J., Withaar, F. K., & Bouma, A. (2004). What is measured by verbal fluency tests in schizophrenia? *Schizophrenia Research*, 69(2–3), 267–276.
- Viswanathan, G. M., Buldyrev, S. V., Havlin, S., Da Luz, M. G. E., Raposo, E. P., & Stanley, H. E. (1999). Optimizing the success of random searches. *Nature*, 401(6756), 911–914.
- Wang, M. Z., & Hayden, B. Y. (2021). Latent learning, cognitive maps, and curiosity. *Current Opinion in Behavioral Sciences*, 38, 1–7.
- Wang, X., & Pleimling, M. (2017). Foraging patterns in online searches. *Physical Review E*, 95(3), 032145.
- Wheeler, M. A., & Roediger, H. L. (1992). Disparate effects of repeated testing: Reconciling Ballard's (1913) and Bartlett's (1932) results. *Psychological Science*, 3(4), 240–245.
- Williams, S. C. (2019). *Neural correlates of adaptive behavior: Structure, dynamics, and information processing* (Publication No. 27543239) [Doctoral dissertation, Indiana University Bloomington]. ProQuest Dissertations Publishing.
- Wimber, M., Alink, A., Charest, I., Kriegeskorte, N., & Anderson, M. C. (2015). Retrieval induces adaptive forgetting of competing memories via cortical pattern suppression. *Nature Neuroscience*, 18(4), 582–589.
- Winstanley, C. A., Robbins, T. W., Balleine, B. W., Brown, J. W., Büchel, C., Cools, R., ... & Seamans, J. K. (2012). Search, goals, and the brain. In P. M. Todd, T. T. Hills, & T. W. Robbins (Eds.), *Cognitive search: Evolution, algorithms, and the brain. Strüngmann Forum reports* (pp. 125–156). MIT Press.