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Random Walks on Semantic Networks Can Resemble Optimal Foraging

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When people are asked to retrieve members of a category from memory, clusters of semantically related items tend to be retrieved together. A recent article by Hills, Jones, and Todd (2012) argued that this pattern reflects a process similar to optimal strategies for foraging for food in patchy spatial environments, with an individual making a strategic decision to switch away from a cluster of related information as it becomes depleted. We demonstrate that similar behavioral phenomena also emerge from a random walk on a semantic network derived from human word-association data. Random walks provide an alternative account of how people search their memories, postulating an undirected rather than a strategic search process. We show that results resembling optimal foraging are produced by random walks when related items are close together in the semantic network. These findings are reminiscent of arguments from the debate on mental imagery, showing how different processes can produce similar results when operating on different representations.

Keywords: semantic fluency, memory search, semantic networks, random walks, optimal foraging

How do people search their memories for information related to a given cue? One classic method for exploring this question, the semantic fluency task, asks people to retrieve as many members of a category as possible in a limited amount of time (Bousfield & Sedgewick, 1944; Thurstone, 1938). This simple task has been used to explore the representations and processes that support semantic memory, and has even been used in clinical settings to study memory deficits in patients with different forms of dementia (Lezak, 1995; Tröster, Salmon, McCullough, & Butters, 1989; Troyer, Moscovitch, Winocur, Leach, & Freedman, 1998). Previous researchers have found that retrieval from semantic memory in fluency tasks tends to be produced in bursts of semantically related words with large pauses between bursts (e.g., Bousfield & Sedgewick, 1944;

Romney, Brewer, & Batchelder, 1993; Troyer, Moscovitch, & Winocur, 1997). For example, Troyer et al. (1997) asked participants to “name as many animals as you can” and observed that the retrieved animals tended to group into clusters (e.g., pets, African animals). The pauses between pairs of retrieved words in the same cluster (e.g., “dog–cat”) were very small when compared with the large pauses between pairs of retrieved words that do not belong to any of the same clusters (e.g., “cat–giraffe”). This pattern of patchy responses led Troyer et al. (1997) to posit that search through semantic memory is comprised of two processes, one process that jumps between clusters related to the given cue and another process that retrieves words within each cluster.

Inspired by this pattern of bursts in retrieval from semantic memory, recent work by Hills, Jones, and Todd (2012) compared search through semantic memory with how animals forage for food. When animals search for food, they must consider the costs and benefits of further depleting their current food source as opposed to searching for a new patch of food. A large subfield in biology called optimal foraging theory has compared animal foraging with ideal strategies (Stephens & Krebs, 1986). In particular, the marginal value theorem shows that an animal’s expected rate of food retrieval is optimal if it stops exploiting the current patch of food when the instantaneous rate (the marginal value) of food acquisition from the current patch is lower than their overall expected rate of food retrieval (Charnov, 1976).

Human search through semantic memory could be considered analogous to how animals search for food, with semantically related clusters playing the role of patches. If this were the case, then the pattern of pauses between pairs of retrieved words could be consistent with optimal foraging theory: Responders should switch clusters when the marginal value of finding

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another item within the current cluster is less than the overall rate of return across memory. Hills et al. (2012) found that human memory search was consistent with this prediction of optimal foraging theory. Based on these results and a comparison of the performance of several different computational models, they proposed that human memory search involves two distinct processes, a “clustering” and a “switching” process, with the strategy for switching being consistent with the marginal value theorem.¹

In this article, we show that behavioral phenomena consistent with a two-stage search process can also be produced by a random walk on a semantic network derived from human word association data. This potentially provides an alternative account of human performance on semantic fluency tasks, and is consistent with previous work linking random walks on semantic networks with memory search (Griffiths, Steyvers, & Firl, 2007; Rhodes & Turvey, 2007; Thompson, Kello, & Montez, 2013). We show that predictions consistent with the results of Hills et al. (2012) are produced by random walks on semantic networks in which items that belong to the same cluster are close together in the network.

By providing an alternative account of the behavioral data that does not explicitly encode aspects of optimal foraging, our analyses suggest that further experiments will be required to determine whether the processes underlying human memory search involve optimal foraging. Furthermore, these results provide a concrete illustration of a theoretical problem for cognitive psychologists that was identified by Anderson (1978) in the context of the mental imagery debate: Different algorithms operating over different representations can produce the same predictions. In this case, a one-stage search process (a random walk) operating on one representation (a semantic network) can resemble a two-stage search process (optimal foraging) operating on another representation (a semantic space). The mimicry may not be complete—it might be possible to construct experiments that differentiate these two accounts—but both models produce key behavioral phenomena from the semantic memory literature.

The remainder of the article is organized as follows. First, we provide relevant background information on the retrieval phenomena predicted by an optimal foraging account of semantic fluency. We then discuss random walks as an alternative framework for modeling memory search, beginning with a model that Hills et al. (2012) considered. This random walk provided a poor fit to human data and did not produce behavior consistent with optimal foraging. We then show that a random walk operating on a different representation—a semantic network based on free-association data—does produce behavior consistent with optimal foraging. An analysis of the two representations on which these random walks are based suggests that the critical difference is that the semantic network better captures the clustering of animals, and a minimal model confirms that a random walk based purely on such a cluster structure produces the key phenomena. We conclude by discussing the implications of our work for understanding the role of representations and algorithms in human foraging behavior and outlining possible directions for future research.

Optimal Foraging as an Account of Semantic Fluency

Optimal foraging theory covers a wide range of situations that a hungry animal might encounter (Stephens & Krebs, 1986), but the most basic scenario involves deciding how to navigate a “patchy” environment for resources. In this environment, food is contained in a set of discrete patches, which become depleted as the animal consumes the food. Staying in a patch thus provides diminishing returns, and the animal has to decide when to leave the patch and seek food elsewhere. The solution is provided by the marginal value theorem (Charnov, 1976), which indicates that the animal should leave the patch when the rate of return for staying drops below the average rate of return in the environment. Hills et al. (2012) suggested that retrieval from semantic memory is analogous to animals foraging for food, in that a patch corresponds to a cluster of semantically related items and acquiring food corresponds to retrieving an item from this cluster.

To investigate whether optimal foraging theory might account for human search through semantic memory, Hills et al. (2012) had people perform a semantic fluency task, in which people were asked to “Name as many animals as you can in 3 min.” They then analyzed the search paths taken through memory, as indicated by the time between the animal names people produced, called the interitem response time (IRT). These names were assigned to the predetermined animal categories identified by Troyer et al. (1997), which were used to analyze patterns in people’s responses: If an item shares a category with the item immediately before it, it is considered part of the same cluster, otherwise that item defines a transition between clusters. For example, given the sequence “dog–cat–giraffe,” “dog” and “cat” are considered elements of the same cluster, whereas “giraffe” is considered the point of transition to a new cluster.

As a first measure of correspondence with optimal foraging theory, the ratio between IRTs and the long-term average IRTs for each participant were examined at different retrieval positions relative to a cluster switch.² Figure 1a displays the results of this analysis. The first word in a cluster (indicated by an order of entry of 1) takes longer to produce than the overall long-term average IRT (indicated by the dotted line), and the second word in a cluster (indicated by 2) takes much less time to produce (reported results of a within-participant paired *t* test were $t(140) = 13.14, p < .001$ and $t(140) = 11.92, p < .001$ for the first and second words, respectively). Furthermore, the IRTs for words preceding a cluster switch (indicated by -1) did not differ significantly from most participants’ own long-term average IRTs (reported results using a one-sample *t* test: 132 of 141 participants were not significantly different, and the nine

¹ Hills et al. (2012) are not the first to suggest that a switching process is involved in memory search—similar ideas appear in previous work (e.g., Raaijmakers & Shiffrin, 1981; Dougherty, Harbison, & Davelaar, 2014).

² Hills et al. (2012) also examined a number of preliminary tests to check their assumptions of memory search in a patchy semantic space. As a test of whether transition points occur when local semantic patches are depleted, the “residual proximity” (or inverse semantic distance) of each word produced was compared to all remaining words not yet produced. They found that items produced immediately before a transition point had a lower residual proximity than items produced immediately after, consistent with their prediction.

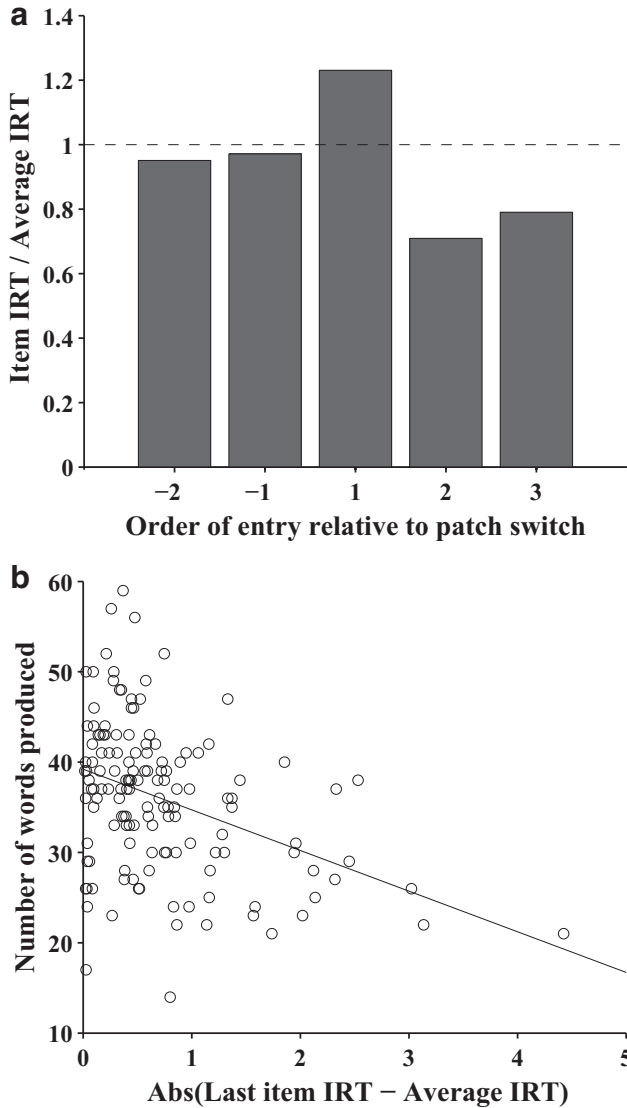


Figure 1. Experimental results of a semantic fluency experiment (free recall from the category of animals) reproduced from Hills et al. (2012). (a) The mean ratio between the interitem response time (IRT) for an item and the participant's long-term average IRT over the entire task, relative to the order of entry for the item (where "1" refers to the relative IRT between the first word in a cluster and the last word in the preceding cluster). The dotted line indicates where item IRTs would be the same as the participant's average IRT for the entire task; (b) the relationship between a participant's deviation from the marginal value theorem policy for cluster departures (horizontal axis) and the total number of words a participant produced.

that were significantly different all had preswitch IRT averages less than their long-term averages). These results are in line with the marginal value theorem, which predicts that IRTs should increase monotonically toward the long-term average IRT prior to a cluster switch, going above this average only when switching to a new cluster.

As a further test of the marginal value theorem's predictions, the absolute difference between the preswitch IRT and long-term average IRT was plotted against the number of words a

participant produced (see Figure 1b). Participants with a larger absolute difference (indicating they either left clusters too soon or too late) produced fewer words, as predicted by the marginal value theorem. Reported results using a linear regression model indicated a significant negative relationship between participants' deviation from the marginal value theorem policy for patch departures and the total number of words the participants produced, with a slope of -5.35 , $t(139) = -5.77$, $p < .001$.

An Initial Comparison of Optimal Foraging and Random Walks

Inspired by the marginal value theorem, Hills et al. (2012) suggested a two-part process model to account for the results of their experiment: when the IRT following a word exceeds the long-term average IRT, search switches from local to global cues. They compared this model to several simpler alternatives, including one in which memory search is simply construed as a random walk over a set of items (called the "one cue-static" model in their article). Random walks have a long history as models of memory (Anderson, 1972), and recent work has shown that random walks on semantic networks can produce a distribution of IRTs in fluency tasks (Rhodes & Turvey, 2007; Thompson et al., 2013) and a pattern of responses in free-association tasks (Griffiths, Steyvers, & Firl, 2007) similar to those produced by people.

The random walk considered by Hills et al. (2012) operated over a set of 771 animals being possible responses in the semantic fluency task. The model assumed that responses people produced were sampled from a distribution based on previous responses, with the probability of each animal given by

$$P(X_i | X_j) \propto S(X_i, X_j)^\beta \quad (1)$$

where $S(X_i, X_j)$ is the similarity between the previous animal response, X_j , and the current animal response, X_i , given by the BEAGLE model of semantic representation (bound encoding of the aggregate language environment; Jones & Mewhort, 2007). In this model, each word is represented by a vector in a semantic space, and the similarity between words is based on the cosine similarity of their vectors. β is a free parameter of the model controlling the saliency (attention weight) assigned to a given cue.

Hills et al. (2012) compared this model with a two-part model that switched between exploring a cluster using a similar random walk and making a larger leap between clusters (called the "combined cue-dynamic" model in their article). In this two-part model, the global switching process was carried out using a generic model of memory retrieval based on the architectures of SAM (search of associative memory; Raaijmakers & Shiffrin, 1981) and ACT-R (adaptive character of thought-rational; Anderson, 1990). This makes it possible to calculate the probability of each participant's sequence of responses under both models, and Hills et al. (2012) found that the two-part model gave a better fit to the human data than the random-walk model.

Another way to evaluate the performance of the random-walk model is to examine whether it can produce the key phenomena of human behavior that are suggestive of optimal foraging: the correspondence between the average IRT and the time at which people switch clusters, and the relationship between deviation

from the marginal value theorem and overall performance (as shown in Figure 1). To examine this, we simulated random walks generating responses via Equation 1 and subjected these responses to the same analyses that Hills et al. (2012) used on their data. We used their reported mean $\beta = 4.34$ in the simulations below.

To connect the output of a simulation (the sequence of items visited by the random-walk model) to the experimental results (i.e., IRTs), we needed to define a method for mapping the sequence of items to IRTs. In our analyses, we considered only the time between first visits to animals, which we denote as $\tau(k)$ for the k th unique animal item seen (out of the K unique animal items visited on the random walk). For example the output of a simulated random walk might be

$$X_0 = \text{"dog"}, X_1 = \text{"cat"}, X_2 = \text{"dog"}, X_3 = \text{"mouse"}.$$

Here, $K = 3$, with $k = 1$ referring to "dog," $k = 2$ referring to "cat," and $k = 3$ referring to "mouse." Our $\tau(k)$ function would return $\tau(1) = 1$, $\tau(2) = 2$, and $\tau(3) = 4$ for this example because we only considered the first time "dog" was visited (at time step $n = 1$). Thus, we defined the IRT between animals k and $k - 1$ in a sequence of nodes visited along a random walk as

$$IRT(k) = \tau(k) - \tau(k - 1) \quad (2)$$

where $\tau(k)$ is the first hitting time of animal $X_{\tau(k)}$. For the above example, the IRT between "mouse" ($k = 3$) and "cat" ($k = 2$) is

$$IRT(3) = \tau(3) - \tau(2) = 4 - 2 = 2.$$

With this mapping defined, we can perform the same set of analyses as Hills et al. (2012) on IRTs between animal words for our random-walker simulations.³

A total of 141 simulated random walks were run for 45 iterations, which was selected so that the average number of animals produced by a simulated random walk was approximately equal to the average number of animals typed by a participant in Hills et al. (2012). Figure 2 shows the results. Consistent with its poor fit to people's responses, the random-walk model did not produce behavior that resembles optimal foraging. Although there was a negative linear relationship between the deviation from the marginal value theorem and overall performance, slope = -31.21 , $t(138) = -4.00$, $p < .001$,⁴ there are few differences between the IRTs and long-term average IRTs, regardless of retrieval position. This latter difference is particularly important when analyzing whether transitions between clusters occur at the point predicted by optimal foraging.

Exploring a Different Semantic Representation

In arguing that people engage in a two-stage process based on optimal foraging theory, Hills et al. (2012) are making a commitment to a particular *algorithm* for memory search. In particular, they show that this algorithm accounts for human behavior better than a random walk. However, in making this comparison they also need to commit to a *representation* of semantic memory—in this case the spatial representation provided by BEAGLE (Jones & Mewhort, 2007). But, as Anderson (1978) pointed out, claims with respect to representation cannot

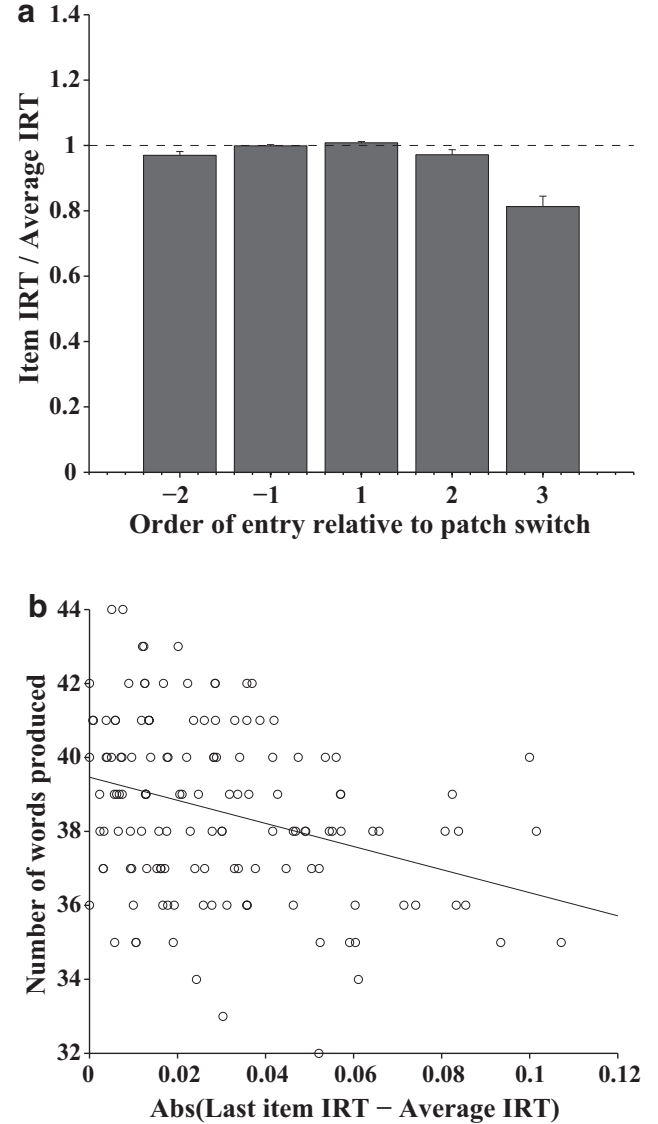


Figure 2. Results from 141 simulations of the random-walk model from Hills et al. (2012), submitted to the same analyses as their human data. (a) The mean ratio between the interitem response time (IRT) for an item and the walker's long-term average IRT over the entire task, relative to the order of entry for the item (where "1" refers to the relative IRT between the first word in a cluster and the last word in the preceding cluster). The dotted line indicates where item IRTs would be the same as the participant's average IRT for the entire task; (b) the relationship between a participant's deviation from the marginal value theorem policy for cluster departures (horizontal-axis) and the total number of words a participant produced.

be evaluated on behavioral evidence alone without assuming a particular algorithm or process on that representation (due to

³ Hills et al., (2012) consider only animals in their search space, we present this method to operate over multidomain spaces more generally.

⁴ We removed outliers from all such analyses, which were defined as foragers whose deviation from the marginal value theorem or the number of words produced were more than three standard deviations from their respective means.

mimicry): With a different representation, a random walk might produce a closer match to human behavior.

Whereas Hills et al. (2012) focused on spatial representations, other researchers in the memory literature have used random walks to capture aspects of human memory search (Griffiths, Steyvers, & Firl, 2007; Rhodes & Turvey, 2007; Thompson et al., 2013) by assuming a different kind of representation: a semantic network (Collins & Loftus, 1975). In a semantic network, nodes and edges in a graph encode words and pairwise associations, respectively.⁵ Previous work has explored how semantic networks can be used to explore questions about the structure of semantic memory (Griffiths, Steyvers, & Firl, 2007; Griffiths, Steyvers, & Tenenbaum, 2007; Romney et al., 1993; Steyvers, Shiffrin, & Nelson, 2004; Steyvers & Tenenbaum, 2005). Following this work, we approximate the structure of semantic memory with a semantic network constructed from people's behavior in a word-association task in which people are given a cue and then list words associated with the cue (Nelson, McEvoy, & Schreiber, 2004). For example, if a participant were told the cue "bed," they might respond with "pillow," "blanket," and "sheet." The result is a semantic network with 5018 nodes, representing the associations between words from "a" to "zucchini." This semantic network has 178 animal nodes from the set of 771 animal words that Hills et al. (2012) operated over. Of these 178 animals, 13 of them did not associate with any other word and so we removed them from this and subsequent analyses (leaving 165 animals for analysis).⁶

A random walk on a semantic network searches memory in the following way. Initially, it starts at the node whose label corresponds to the cue. It moves to a new node by following an edge, selected at random, from the current node to the new node. A random walk on a semantic network could retrieve items in a patchy manner, appearing to make deliberate switches between clusters, if the clusters correspond to densely linked sets of nodes with few links between them. Thus, if the clusters that appear in people's responses are reflected in the structure of the semantic network, this nonstrategic search process might be sufficient to capture the phenomena reported by Hills et al. (2012).

Other than the network, there are two other steps to defining a random walk: (a) defining at what node the random walk starts (or a probability distribution over nodes), and (b) defining the probability distribution for transitioning from one node to the next node (a transition-probability matrix). We assumed that the random walk started at the node that represented cue C given to the participant. So, to capture the results of Hills et al. (2012), we assumed that C was "animal," and $X_0 = l^{-1}(C)$, where $l(\cdot)$ was a function whose input was a node and output was its corresponding label, and $l^{-1}(\cdot)$ is the inverse function, whose input was the label and its output was the node with that label. We explored four possible transition-probability matrices defined by the orthogonal combination of two factors: whether the probability of transitioning out of a node was *uniform* or *weighted* over its edges and whether there was a nonzero probability of jumping back to the node corresponding to the cue.

The first factor was whether the probability of transitioning out of a node was uniform over its outgoing edges from the current node (as discussed in the previous example) or weighted, allowing the model to represent the degree of association between two items. In the case of the weighted model, the probability of

transitioning from the current node to a new node is proportional to the frequency that the label of the new node was said by a participant given the current node as a cue in the word-association database (Nelson et al., 2004). Formally, the associations between a set of n items can be represented as a $n \times n$ matrix \mathbf{L} , where $L_{ij} = 1$ when item j was associated with item i and was 0 otherwise. A random walk over these n items was defined by a matrix \mathbf{M} of transition probabilities, where M_{ij} denoted the conditional probability of jumping to item i , given that the random walk was currently at item j . In the uniform model, this was

$$M_{ij} = \frac{L_{ij}}{\sum_{k=1}^n L_{kj}}. \quad (3)$$

The denominator is called the *out-degree* of node j , or the number of items that are associates of item j and so it is the number of possible items that the random walk could move to from node j . For the weighted model, L_{ij} is proportional to the number of times that i was an associate of j . The weighted model can capture that some associations (e.g., "dog" and "cat") are stronger than others (e.g., "dog" and "house").

The second factor is either nonjumping, where there is no effect of the cue besides for initializing the random walk, or jumping, where at each time step, the model "jumps" back to the cue with probability p , but otherwise (with probability $1 - p$) the model transitions in the same way as described above.⁷

In sum, we explored four different random-walk models that were formed by combining two factors: the probability of transitioning, whether the edges are uniform or weighted and whether the random walk randomly jumps back to the cue (jumping) or not (nonjumping). Formally, they are all defined by the following equation

$$P(X_{n+1} | C = \text{"animal"}, X_n = x_n) = pP(X_{n+1} | X_n = l^{-1}[\text{"animal"}]) + (1 - p)P(X_{n+1} | X_n = x_n) \quad (4)$$

⁵ Technically, any random walk on a discrete set of objects can be interpreted as a random walk on a graph. From this perspective, the random walk considered by Hills et al. (2012) could be viewed as a random walk on a semantic network. However, the probabilities of moving between nodes on this graph were derived from the spatial representation used in BEAGLE, which places constraints on what kinds of conditional probabilities (and graph structures) are possible (for a discussion of these constraints, see Tversky, 1977; Griffiths, Steyvers, & Tenenbaum, 2007). In particular, low-dimensional spatial representations constrain the number of items to which an item can be the nearest neighbor (Tversky & Hutchinson, 1986)—a property that might be relevant to the behavior of a random walk.

⁶ Our random-walk models operate over all 5018 nodes in the semantic network, however our $\tau(k)$ function operates over just these 165 animals.

⁷ We note this is a qualitatively different operation than the proposal of "jumping" between different search cues made by Hills et al. (2012). Rather than reflecting a strategic decision to switch between clusters, the jumps are executed at random and simply "prime" the search process by returning to the initial state. In simulations not presented in the article, we also examined the consequences of jumping to random nodes—a process which is more similar to the move from local to global cues in the model proposed by Hills et al. (2012), and has precedent in other work on random walks and semantic memory (Goñi et al., 2010, 2011). However, this jumping process produces qualitatively similar results to those described in the main text.

where $P(X_{n+1}|X_n)$ is defined by Equation 3, with L defined according to whether the model is uniform or weighted, and $\rho = 0$ when the model was nonjumping or $0 < \rho \leq 1$ when the model was jumping.

A direct quantitative comparison between these models and the models considered by Hills et al., (2012) is difficult, as there are different numbers of animals in the free-association data and in the BEAGLE representation. This makes comparison hard because the probabilities assigned to participant responses by each model are determined in part by the number of possible responses (roughly speaking, the more animals in the model, the less probability the model assigned to each animal). Instead, we perform qualitative comparisons of these models the same way we did for the random walk earlier in the article.

A total of 141 simulated random walks were run for each of the four models. Each simulation was run for 2000 iterations, which was selected so that the average number of animals produced by a simulated random walk was approximately equal to the average number of animals typed by a participant in Hills et al. (2012). On average, each participant responded with 36.8 animals, and an average of 33.5, 42.5, 23.8, and 30.9 animals were produced by the uniform nonjumping, uniform jumping, weighted nonjumping, and weighted jumping random-walk models, respectively. We expected the jumping models to produce more animals than the nonjumping models because “jumps” got the model away from nodes already visited by the random walk. In addition, we expected slightly fewer animals to be produced by the random-walk models than participants because of the small number of animals included in the semantic network (most people have probably encountered more than 165 animals). For the jumping models, we selected the probability of jumping on a given trial, ρ , to be 0.05. Other values for ρ produced similar results (assuming the value was small).

Figure 3 shows the results of analyzing the simulations of the four random-walk models for optimal foraging-like behavior in the same way that Hills et al., (2012) performed for participants in their experiment.⁸ In the left column of Figure 3 is the average ratio of the IRT of an item relative to its distance to the closest cluster switch (“order of entry”), and, the overall average IRT for each random-walk model. Like people, the first item in a cluster (indicated by 1) had a significantly longer IRT than the overall average IRT, $t(140) > 17$, $p < .001$, for all four models, and the second item in a cluster (indicated by 2) had a significantly shorter IRT than the overall average IRT, $t(140) < -15$, $p < .001$, for all four models.⁹ In addition, the IRTs for words preceding a cluster switch (indicated by -1) were not significantly different from most walkers’ long-term average IRTs.¹⁰ This pattern of results is consistent with the results of participants in Hills et al.’s (2012) experiment, the marginal value theorem, and optimal foraging. Each time the IRT increased dramatically (at 1) and then decreased dramatically (at 2), one might have been tempted to suggest that the model “found” another “patch” of relevant items in the semantic network. However, the model didn’t use search strategies. It was simply walking randomly over the semantic network and emitting the labels of nodes that it visited. Thus, a simple process over a structured representation is sufficient to capture optimal foraging-like behavior.

The right column of Figure 3 shows the marginal value theorem’s cluster-switching policy, where the absolute difference be-

tween the preswitch IRT and long-term average IRT was plotted against the number of words a random walker produced, along with a regression line through this data (as in Figure 1b). Across all four models, walkers with a larger absolute difference (indicating they either left clusters too soon or too late), produced fewer words—a linear regression model revealed a significant negative relationship between axes for each of the four models: slope = -0.19 , $t(137) = 2.51$, $p < .05$, slope = -0.21 , $t(137) = 1.98$, $p < .05$, slope = -0.10 , $t(135) = 3.25$, $p < .05$, slope = -0.09 , $t(137) = 2.15$, $p < .05$ for the uniform nonjumping, uniform jumping, weighted nonjumping, and weighted jumping models, respectively. We were intrigued that each of the models produced the basic phenomena that were considered evidence for the use of the marginal value theorem in memory search. These results show that behavior consistent with following the marginal value theorem can be produced by surprisingly simple search algorithms, at least when measured along these metrics. In the following sections, we turn to examining how the structure of semantic memory affects the behavior of these random walks.

The Importance of Clustering

Our results so far show that a random walk on a semantic network derived from free associations produces phenomena suggestive of optimal foraging, whereas a random walk on a spatial representation generated by BEAGLE (Jones & Mewhort, 2007) does not. This raises a natural question: Why? What is the critical difference between these two representations?

To address this question, we examined whether the similarity between items in these two representations reflects the clusters used by Troyer et al. (1997). According to the semantic network, the similarity between the animals corresponding to nodes i and j was encoded as $s_{ij} = \exp\{-d_{ij}\}$, where d_{ij} is the shortest path distance between the nodes i and j in the semantic network. To derive similarities from the clusters, we used an additive clustering model (Shepard & Arabie, 1979) in which the (nonexclusive) clusters from Troyer et al. (1997) were interpreted as features. To do so, we formed a 165×165 similarity matrix \mathbf{S} . According to additive clustering, the similarity matrix is defined as

$$\mathbf{S} = \mathbf{FWF}' \quad (5)$$

where \mathbf{F} is the matrix of clusters interpreted as features ($\mathbf{F}_{ac} = 1$ when animal a is in cluster c), and \mathbf{W} is a diagonal weight matrix, whose elements are non-negative and represent the psychological weights of

⁸ We also examined “residual proximity,” finding each of the models to follow the prediction that the last word in a patch has a lower residual proximity than the first word in a patch, $t(140) = -2.4$, $p < .05$ for all four models.

⁹ The introduction of jumps primarily reduces the difference for IRTs before (at -2) and after a cluster switch (at 2 and 3), while increasing the amount of time it takes to find the first item in a cluster. This can be explained by the model randomly jumping back to the cue anywhere along the search path, making it difficult to find a new animal, yet once one is found, there are more unseen animals left to find nearby.

¹⁰ The IRT for words preceding cluster switches (indicated by -1) of 140, 138, 139, and 138 out of 141 walkers were not significantly different for the uniform nonjumping, uniform jumping, weighted nonjumping, or weighted jumping models respectively, and all of the walkers that were significantly different had preswitch IRT averages less than their long-term averages for each of the four models.

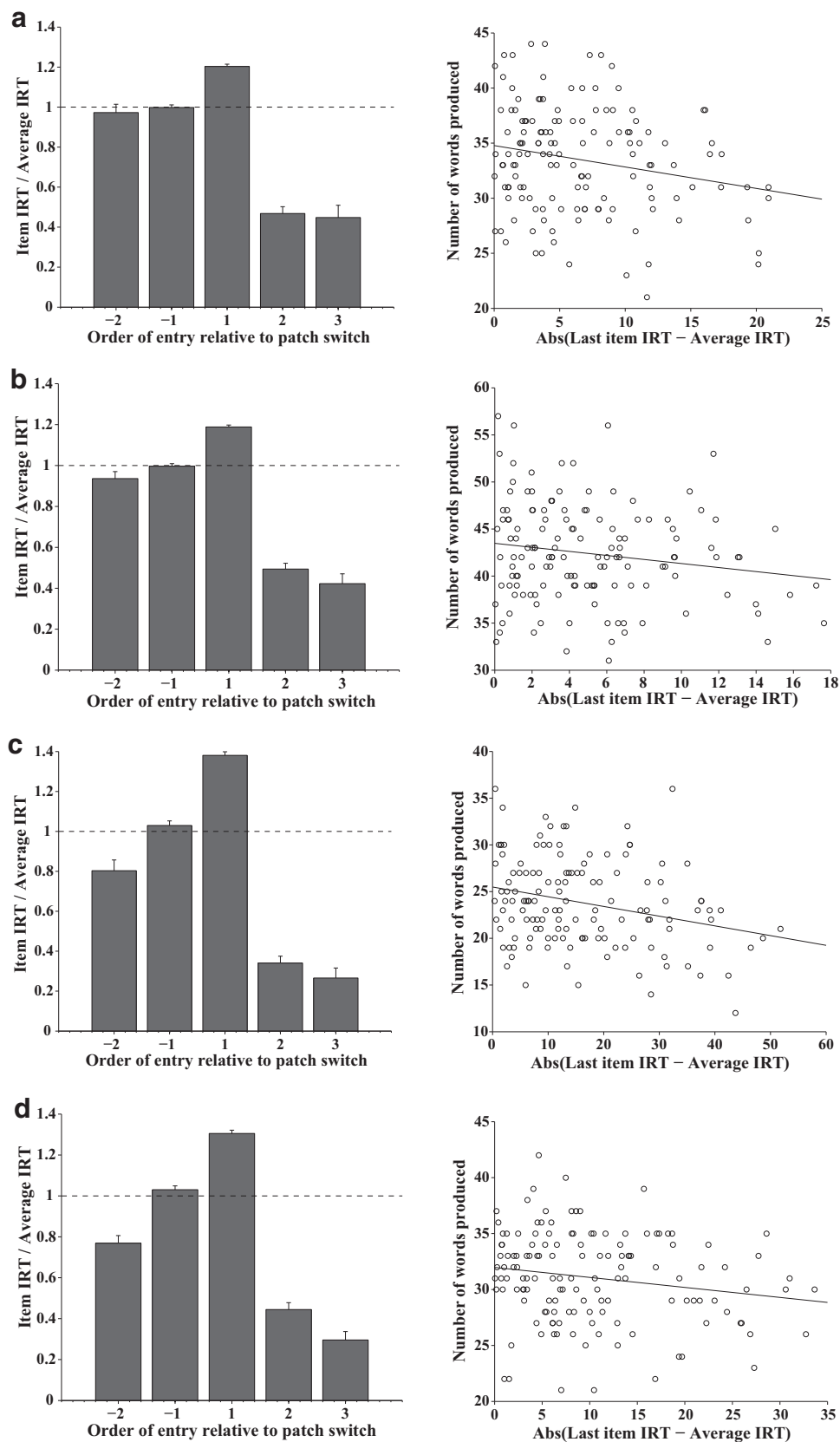


Figure 3 (opposite)

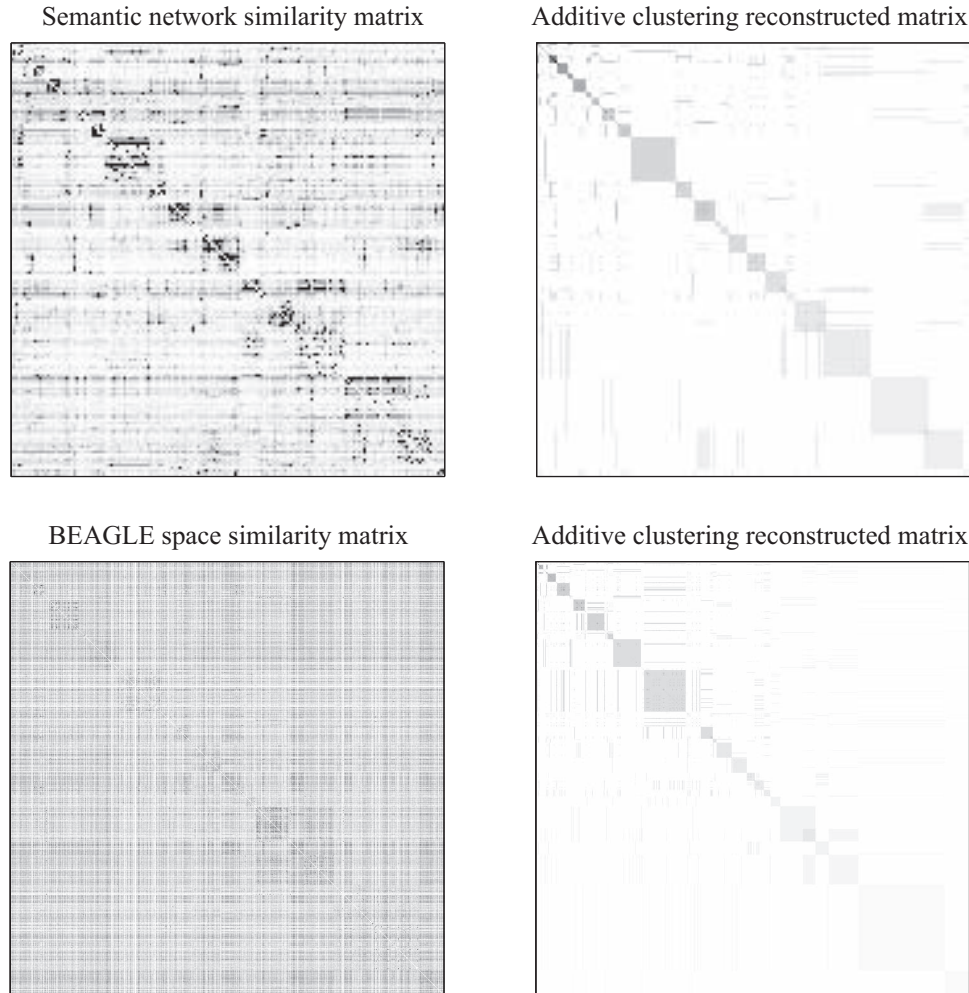


Figure 4. (Top row) A visualization of the similarity between pairs of animals in the semantic network (left panel) and an additive clustering model (right panel), where darker colors represent stronger similarities (bottom row). A visualization of the BEAGLE animal similarity space (left panel) and an additive clustering model (right panel). The rows and columns of each matrix were reordered to display animals in the clusters with largest weight first.

the clusters. We used the 22 animal clusters defined by Troyer et al. (1997) to define \mathbf{F} . We inferred \mathbf{W} by maximizing the posterior distribution of reconstructing \mathbf{S} based on graph distances using additive clustering, assuming a Gaussian prior on \mathbf{W} and a Gaussian reconstruction error (as outlined in Navarro & Griffiths, 2008).

The top row of Figure 4 shows the graph-based \mathbf{S} matrix and the \mathbf{S} matrix reconstructed using additive clustering. Visual inspection of the block structure in both \mathbf{S} matrices confirms that they are very similar and provides evidence that the semantic network

implicitly encodes the clusters. The distance between the nodes corresponding to animals in the same cluster is smaller than the distance between animals in different clusters and the retrieval process depends (implicitly or explicitly) on this distance. This may be why a random walk on a semantic network can produce behavior that resembles optimal foraging.

By comparison, the representation used in the random walk evaluated by Hills et al. (2012) did not show the same pattern of clustering. We used the same additive-clustering technique on the

Figure 3 (opposite). Results after 141 simulations for the four random-walk models: (b) the uniform transition model with no jumps, (a) the weighted transition model with no jumps, (d) the uniform transition model with a jump probability of 0.05, and (c) the weighted transition model with a jump probability of 0.05. The left column displays the mean ratio between IRT for an item and the walker's long-term average IRT over the entire task, relative to the order of entry for the item (where 1 refers to the relative IRT between the first word in a cluster and the last word in the preceding cluster). The dotted line indicates where item IRTs would be the same as the walker's average IRT for the entire task. The right column displays the relationship between a walker's deviation from the marginal value theorem policy for cluster departures (horizontal-axis) and the total number of words a walker produced.

similarity data from BEAGLE, examining how well the similarity data could be predicted from the cluster membership of different animals. The bottom row of Figure 4 shows the results: there was only a weak signature of the animal clusters in these data. Consequently, the poor performance of this model could be a result of the underlying representation not encoding a clear cluster structure.

These results suggest that the critical difference between these two representations may be the extent to which they capture the cluster structure of animals. Because items that are in the same cluster are close in the semantic network, a random walk tends to stay within clusters and occasionally switches between clusters, creating the illusion of a two-stage search process. To evaluate this idea, and to demonstrate that the performance of our model does not depend on any of the specifics of the free-association data from which our semantic network was formed, we conducted a further simulation using a minimal random-walk model. In this model, we assumed that the probability of a transition from item j to item i is given by

$$\mathbf{L}_{ij} = \begin{cases} 0 & i = j \\ (1-p)/C_j & i \text{ and } j \text{ are in the same cluster} \\ p/(n-C_j-1) & i \text{ and } j \text{ are not in the same cluster} \end{cases} \quad (6)$$

where C_j is the number of items that belong to the same cluster as item j (excluding item j) and n is the total number of items. This model only makes use of the cluster structure, assigning a high probability to transitions within a cluster when p is small, but uses no other information about the items to determine the transition probabilities.

The random walk was run over the subset of 165 animals from the semantic network used in our previous simulation, and p was determined by calculating the average probability of making a transition outside a cluster in the uniform nonjumping random walk based on the word-association network. We ran 141 simulations for a total of 45 steps each, and submitted them to the same analyses as Hills et al. (2012). The results are shown in Figure 5. The left column shows the key phenomena associated with optimal foraging, with the first word in a patch taking significantly longer to produce on average, $t(140) = 9.49$, $p < .001$, and the second word taking much less time to produce than the long-term mean, $t(140) = -11.11$, $p < .001$. The right column of Figure 5 examines consistency with the cluster-leaving policy indicated by the marginal value theorem, where again we find that walkers with a larger absolute difference, indicating they either left clusters too soon or too late) produced fewer words (a linear regression model found a significant negative relationship between axes: slope = -4.88 , $t(132) = 4.09$, $p < .001$).

The fact that this minimal model produced behavior similar to optimal foraging suggests that random walks can mimic a two-stage search process, provided they are on a representation that captures the underlying cluster structure. This suggests the success of the random-walk model using the semantic network based on free associations in producing behavior that resembles optimal foraging, and the failure of the random walk using the BEAGLE representation considered by Hills et al. (2012) may be considered a consequence in the extent to which they capture this cluster structure.

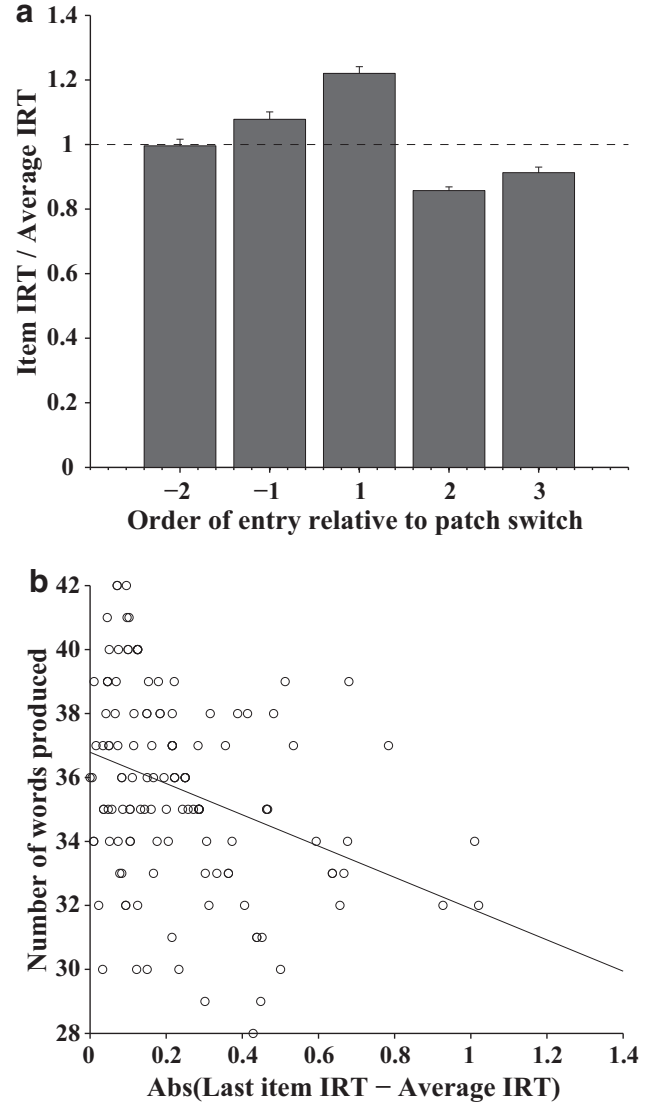


Figure 5. Results for the minimal model on our semantic network with p estimated from the uniform transition word association matrix. (a) The mean ratio between the IRT for an item and the walker's long-term average IRT over the entire task, relative to the order of entry for the item (where 1 refers to the relative IRT between the first word in a patch and the last word in the preceding patch). The dotted line indicates where item IRTs would be the same as the walker's average IRT for the entire task; (b) the relationship between a walker's deviation from the marginal value theorem policy for patch departures (horizontal axis) and the total number of words a walker produced.

Discussion

In this article, we examined two potential explanations for why people show optimal foraging-like behavior when they retrieve items from semantic memory. Both explanations produced behavior consistent with the predictions of optimal foraging, but they proposed that very different representations and processes are responsible for this behavior. Hills et al. (2012) suggested that semantic memory is based on spatial representations and search is

a dynamic process, retrieving items from one cluster at a time and switching between clusters when the retrieval rate falls below a threshold. We proposed an alternative explanation, that is, semantic memory is represented by a network and search is simply a random walk on the network. In support of this proposal, we showed that predictions consistent with the results of Hills et al. (2012) are produced by a random-walk model on a network where semantically related items are close together in the network.

In the remainder of the article we discuss some of the implications of our results. In particular, the observation that different algorithms operating on different representations can yield similar predictions echoes previous arguments about the challenges of identifying cognitive representations and processes (Anderson, 1978). We explore this connection and highlight some directions for future research to try and shed light on the processes that underlie performance on semantic fluency tasks.

Representations and Algorithms

Taken together, our simulations showed that the behavior in semantic fluency tasks that Hills et al. (2012) viewed as evidence for optimal foraging is also predicted by a random walk on a semantic network. This behavior depends on the representation used by the random-walk model, which we find crucial to note: A random walk on a semantic network produces optimal foraging behavior, but a random walk on corresponding spatial representations does not. Consequently, it seems that there is something special about the semantic network representation that allows the simple random walk to appear similar to optimal foraging.

Finding that different algorithms operating on different representations can produce the same behavior might seem surprising, but has a precedent in cognitive psychology. The mental imagery debate (e.g., Kosslyn, 1994; Pylyshyn, 1973) depended crucially on this issue—whether there are effective ways of identifying the algorithms and representations that human minds employ. Anderson (1978) convincingly argued that we should not be surprised to find cases in which algorithms and representations that seem quite different nonetheless end up producing similar behavior—such cases are the rule, rather than the exception. In fact, for a sufficiently rich set of algorithms and representations, we can always find algorithm–representation pairs that cannot be discriminated based purely on behavior.

The situation illustrated by our analyses is not necessarily as extreme as the cases that Anderson (1978) considered, but they do illustrate one of the fundamental challenges of cognitive psychology: Possible psychological representations and mechanisms are always underdetermined by the available behavioral data, and even behavior that seems like the signature of one mechanism can sometimes be produced by others. In this case, further experiments may be able to discriminate between optimal foraging and random walks, but these experiments will have to be specifically designed to distinguish between these two accounts rather than motivated by the predictions of one account alone.

Future Directions

Demonstrating that random-walk models can produce behavior consistent with optimal foraging in semantic fluency tasks generates some interesting directions for future research. As mentioned

in the previous section, having two competing accounts of the same phenomena suggests that the next step in exploring semantic fluency is designing an experiment that distinguishes between these accounts. One way to do this might be to explore the extent to which human memory search really is strategic—offering people the opportunity to get a “hint” (say, an example category member) might provide the way to do this, as it would be possible to examine whether people seek hints at the moments predicted by the marginal value theorem.

An alternative approach to distinguish these models is considering whether the optimal foraging account can also predict results that the random-walk model has previously been used to explain. One such result is the correspondence of word fluency with PageRank (Griffiths, Steyvers, & Firl, 2007), something that follows directly from the random-walk account, but might be more challenging to account for in terms of optimal foraging. Likewise, additional support for optimal foraging in memory has been found that directly measures variables associated with working-memory capacity and relates them to features associated with the search process (Hills & Pachur, 2012; Hills, Mata, Wilke, & Samanez-Larkin, 2013). Accordingly, these findings provide future tests for the random-walk account.

Another direction for future research would be to consider how these different proposals fare in accounting for changes in semantic fluency in clinical populations. Given that conditions such as Alzheimer’s and Parkinson’s diseases differentially affect clustering and switching (Borge-Holthoefer, Moreno, & Arenas, 2011; Johns et al., 2013; Lezak, 1995; Tröster et al., 1989; Troyer et al., 1997, 1998), comparing what degradations to the models are needed to explain the differential changes in different clinical populations might help to answer practical as well as theoretical questions about human memory.

Finally, exploring some of the nuances of optimal foraging as an account for human memory search is likely to be productive. Human foraging behavior has been examined in a few other domains, including information foraging (Pirulli & Card, 1999) and searching for resources in a simulated spatial environment (e.g., Cain, Vul, Clark, & Mitroff, 2012; Hutchinson, Wilke, & Todd, 2008; Kalff, Hills, & Wiener, 2010; Wolfe, 2013). In particular, researchers conducting studies in simulated environments have investigated the strategies people use in multiple-target search and have examined whether searchers adapt their strategies based on the target distribution statistics. The common finding is that people are in fact sensitive to the resource distributions of their environment, spending more time in resource-dense patches as predicted by optimal foraging theory. However, their actual departure times from these patches tend to be at nonoptimal rates (e.g., dependent on patch quality and not the long-term average rate of return, as predicted by the marginal value theorem). It would be interesting to see whether modifying the optimal foraging model considered by Hills et al. (2012) to produce behavior more consistent with human search in these other domains would increase or decrease its fit to the data from semantic fluency tasks.

Conclusion

Identifying and retrieving information relevant to a cue is one of the basic capabilities of the human memory system. Under-

standing how people solve the task of searching this vast store of information is likely to give us insight, not just into the human mind, but into how to build better artificial information retrieval systems. Optimal foraging and random walks on semantic networks offer two quite different accounts of this process—one based on an intelligent search strategy, the other on a rich representational framework. Both algorithms also have links to other disciplines, offering links to literatures in biology and computer science, respectively. That both accounts can produce similar behavior is surprising, but also exciting, in that it creates new opportunities to explore these connections more deeply and develop a more complete picture of this remarkable human capacity.

References

- Abbott, J. T., Austerweil, J. L., & Griffiths, T. L. (2012). Human memory search as a random walk in a semantic network. *Advances in Neural Information Processing Systems*, 25, 3050–3058.
- Anderson, J. R. (1972). FRAN: A simulation model of free recall. *Psychology of Learning and Motivation*, 5, 315–378.
- Anderson, J. R. (1978). Arguments concerning representations for mental imagery. *Psychological Review*, 85, 249–277.
- Anderson, J. R. (1990). *The adaptive character of thought*. Hillsdale, NJ: Erlbaum.
- Borge-Holthoefer, J., Moreno, Y., & Arenas, A. (2011). Modeling abnormal priming in Alzheimer's patients with a free association network. *PloS One*, 6 e22651.
- Bousfield, W. A., & Sedgewick, C. H. W. (1944). An analysis of sequences of restricted associative responses. *Journal of General Psychology*, 30, 149–165.
- Cain, M. S., Vul, E., Clark, K., & Mitroff, S. R. (2012). A Bayesian optimal foraging model of human visual search. *Psychological Science*, 23, 1047–1054.
- Charnov, E. (1976). Optimal foraging, the marginal value theorem. *Theoretical Population Biology*, 9, 129–136.
- Collins, A. M., & Loftus, E. F. (1975). A spreading-activation theory of semantic processing. *Psychological Review*, 82, 407–428.
- Dougherty, M. R., Harbison, J. I., & Davelaar, E. J. (2014). Optional stopping and the termination of memory retrieval. *Current Directions in Psychological Science*, 23, 332–337.
- Goñi, J., Arrondo, G., Sepulcre, J., Martincorena, I., de Mendizábal, N. V., Corominas-Murtra, B., . . . Villoslada, P. (2011). The semantic organization of the animal category: Evidence from semantic verbal fluency and network theory. *Cognitive Processing*, 12, 183–196.
- Goñi, J., Martincorena, I., Corominas-Murtra, B., Arrondo, G., Ardanza-Trevijano, S., & Villoslada, P. (2010). Switcher-random-walks: A cognitive-inspired mechanism for network exploration. *International Journal of Bifurcation and Chaos*, 20, 913–922.
- Griffiths, T. L., Steyvers, M., & Firl, A. (2007). Google and the mind. *Psychological Science*, 18, 1069–1076.
- Griffiths, T. L., Steyvers, M., & Tenenbaum, J. B. (2007). Topics in semantic representation. *Psychological Review*, 114, 211–244.
- Hills, T., Jones, M., & Todd, P. (2012). Optimal foraging in semantic memory. *Psychological Review*, 119, 431–440.
- Hills, 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, 2396.
- Hills, T., & Pachur, T. (2012). Dynamic search and working memory in social recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 38, 218–228.
- Hutchinson, J., Wilke, A., & Todd, P. M. (2008). Patch leaving in humans: Can a generalist adapt its rules to dispersal of items across patches? *Animal Behaviour*, 75, 1331–1349.
- Johns, B. T., Taler, V., Pisoni, D. B., Farlow, M. R., Hake, A. M., Kareken, D. A., . . . Jones, M. N. (2013). Using cognitive models to investigate the temporal dynamics of semantic memory impairments in the development of Alzheimer's disease. In R. West, & T. Stewart (Eds.), *Proceedings of the 12th International Conference on Cognitive Modeling* (pp. 23–28). Ottawa, ON, Canada: Carleton University.
- Jones, M. N., & Mewhort, D. J. K. (2007). Representing word meaning and order information in a composite holographic lexicon. *Psychological Review*, 114, 1–37.
- Kalff, C., Hills, T., & Wiener, J. (2010). Human foraging behavior: A virtual reality investigation on area restricted search in humans. In S. Ohlsson, & R. Catrambone (Eds.), *Proceedings of the 32nd Annual Conference of the Cognitive Science Society* (pp. 168–173). Austin, TX: Cognitive Science Society.
- Kosslyn, S. M. (1994). *Image and brain: The resolution of the imagery debate*. Boston, MA: MIT Press.
- Lezak, M. (1995). *Neuropsychological assessment*. New York, NY: Oxford University Press.
- Navarro, D. J., & Griffiths, T. L. (2008). Latent features in similarity judgments: A nonparametric Bayesian approach. *Neural Computation*, 20, 2597–2628.
- Nelson, D., McEvoy, C., & Schreiber, T. (2004). The University of South Florida free association, rhyme, and word fragment norms. *Behavior Research Methods*, 36, 402–407.
- Pirolli, P., & Card, S. (1999). Information foraging. *Psychological Review*, 106, 643–675.
- Pylyshyn, Z. W. (1973). What the mind's eye tells the mind's brain: A critique of mental imagery. *Psychological Bulletin*, 80, 1–24.
- Raaijmakers, J., & Shiffrin, R. (1981). Search of associative memory. *Psychological Review*, 88, 93–134.
- Rhodes, T., & Turvey, M. T. (2007). Human memory retrieval as Lévy foraging. *Physica A: Statistical Mechanics and its Applications*, 385, 255–260.
- Romney, A. K., Brewer, D. D., & Batchelder, W. H. (1993). Predicting clustering from semantic structure. *Psychological Science*, 4, 28–34.
- Shepard, R. N., & Arabie, P. (1979). Additive clustering: Representation of similarities as combinations of discrete overlapping properties. *Psychological Review*, 86, 87–123.
- Stephens, D., & Krebs, J. (1986). *Foraging theory*. Princeton, NJ: Princeton University Press.
- Steyvers, M., Shiffrin, R., & Nelson, D. (2004). Word association spaces for predicting semantic similarity effects in episodic memory. In A. F. Healy (Ed.), *Experimental cognitive psychology and its applications: Festschrift in honor of Lyle Bourne, Walter Kintsch, and Thomas Landauer*, 237–249. Washington, DC: American Psychology Association.
- Steyvers, M., & Tenenbaum, J. (2005). The large-scale structure of semantic networks: Statistical analyses and a model of semantic growth. *Cognitive Science*, 29, 41–78.
- Thompson, G. W., Kello, C. T., & Montez, P. (2013). Searching semantic memory as a scale-free network: Evidence from category recall and a wikipedia model of semantics. In M. Knauff, N. Sebanz, M. Pauen, I. Wachsmuth (Eds.), *Proceedings of the 35th Annual Meeting of the Cognitive Science Society*. Austin, TX: Cognitive Science Society.
- Thurstone, L. (1938). Primary mental abilities. *Psychometric Monographs*.
- Tröster, A., Salmon, D., McCullough, D., & Butters, N. (1989). A comparison of the category fluency deficits associated with Alzheimer's and Huntington's disease. *Brain and Language*, 37, 500–513.
- 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, 138–146.

- Troyer, A. K., Moscovitch, M., Winocur, G., Leach, L., & Freedman, M. (1998). Clustering and switching on verbal fluency tests in Alzheimer's and Parkinson's disease. *Journal of the International Neuropsychological Society*, 4, 137–143.
- Tversky, A. (1977). Features of similarity. *Psychological Review*, 84, 327–352.
- Tversky, A., & Hutchinson, J. (1986). Nearest neighbor analysis of psychological spaces. *Psychological Review*, 93, 3–22.
- Wolfe, J. M. (2013). When is it time to move to the next raspberry bush? Foraging rules in human visual search. *Journal of Vision*, 13, 1–17.

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