Human memory search as a random walk in a semantic network

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Introduction

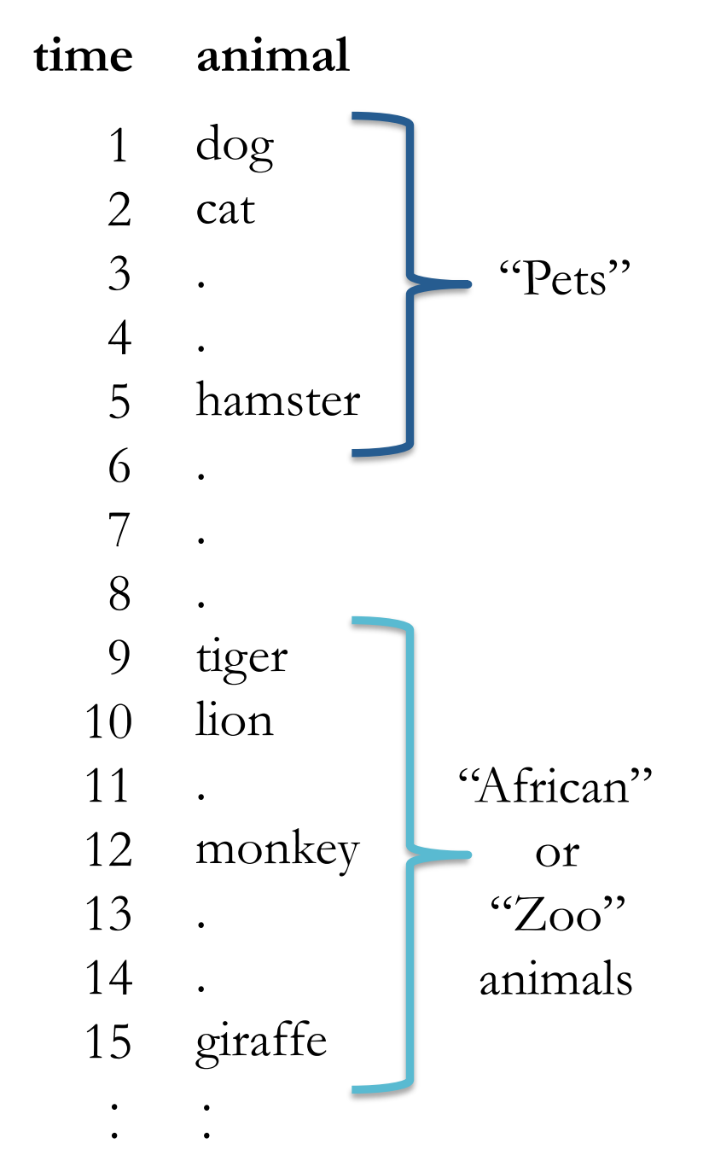
What are the representations and algorithms underlying human memory search?

When people search their memory, clusters of semantically related items tend to be retrieved together [1]. A recent proposal suggests these patterns reflect an optimal foraging policy, with people searching for items distributed in memory in a manner similar to animals searching for food in patchy environments [2]. This explanation is relatively complex, assuming two separate processes and a strategic decision to switch between them.

We show that these results can be reproduced by a random walk on a semantic network, which offers a simpler alternative explanation and provides further support for the idea that memory search might just be a random walk over a structured representation.

Semantic fluency and optimal foraging

Semantic fluency task: Name as many animals as you can in 3 minutes.



time	animal
1	dog
2	cat
3	.
4	.
5	hamster
6	.
7	.
8	.
9	tiger
10	lion
11	.
12	monkey
13	.
14	.
15	giraffe
:	:

“Pets”

“African” or “Zoo” animals

Two-part memory retrieval process [1, 2]

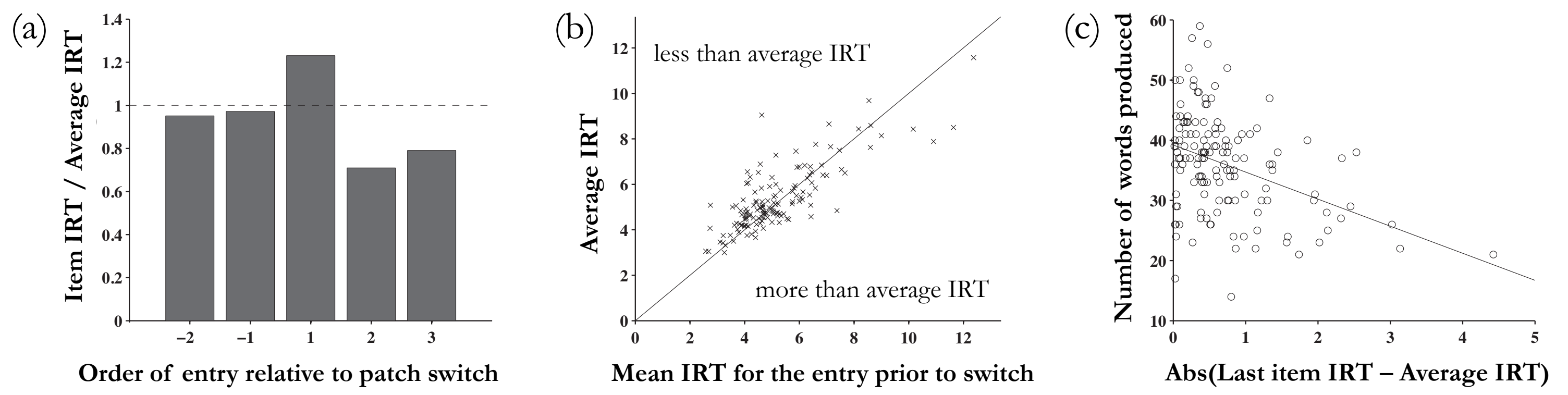
clustering: produce words from the current semantic subcategory using local cues.

switching: transition from the current to a different subcategory using global cues.

Optimal foraging policy for memory search [2]

Leave a “patch” in memory (ie: semantically related cluster) when the instantaneous rate of finding more relevant items falls below the expected rate of searching elsewhere in memory.

Human results from Hills et al. [2] animal naming task



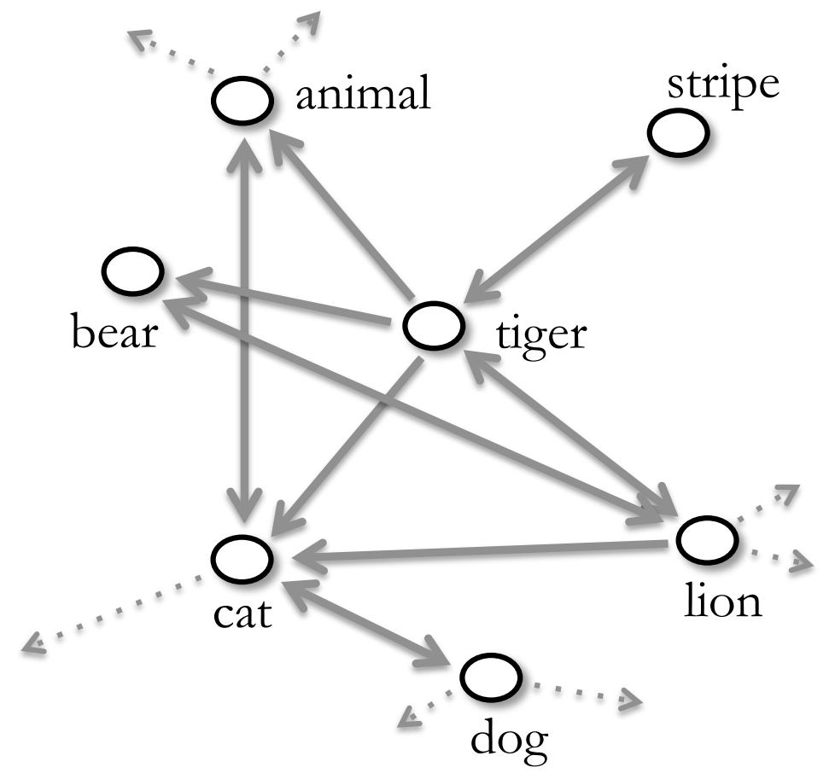
(a) IRTs increase towards the long-term average IRT up until a patch switch, going above it only for patch switches (indicated by “1”) as it takes extra time to find a new patch.
(b) The majority of participants’ pre-switch IRTs take less time than their long-term average IRT.
(c) When participants leave a patch too late or too soon, they produce fewer words.

These results are consistent with the optimal foraging policy for memory search.

Structure of semantic memory

A *semantic network* represents the relationships between words (or concepts) as a directed graph, where each word is represented as a node and nodes are connected by an edge if they are associated in some manner.

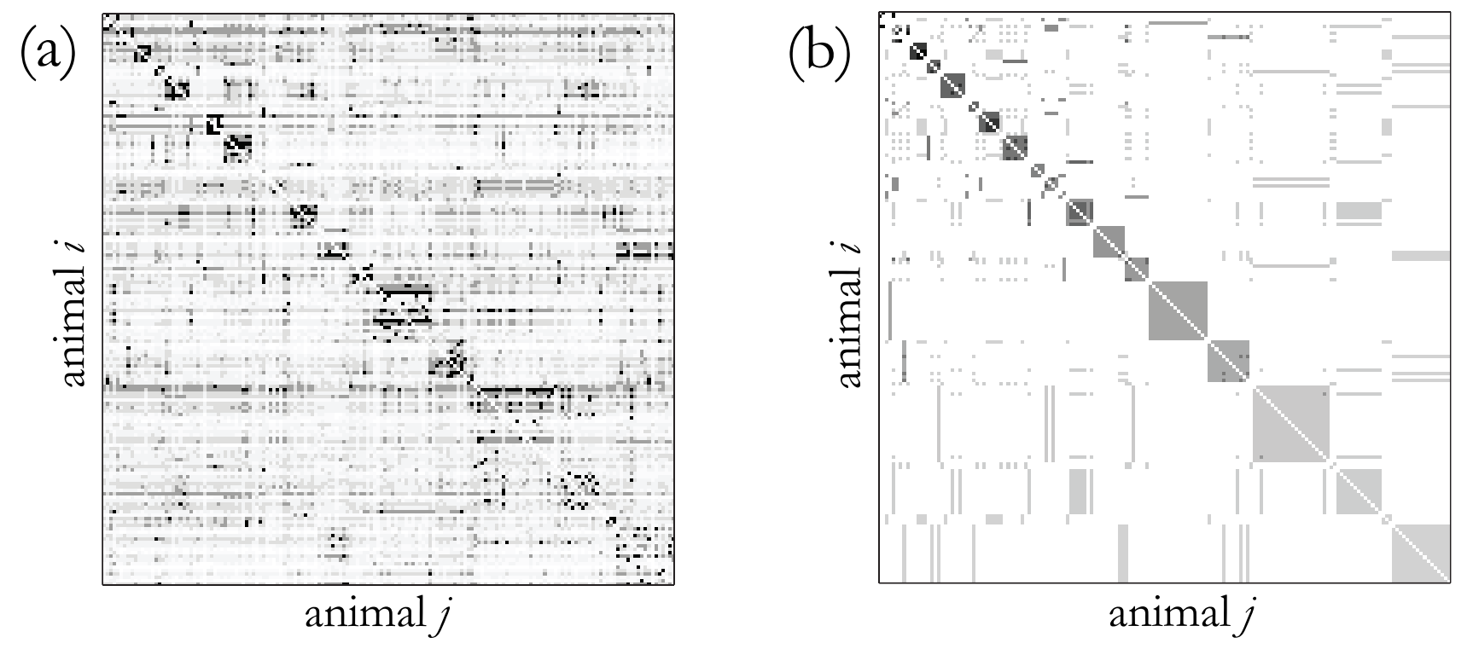
We use a network with 5018 nodes derived from a word association task [3], in which people were asked to list the words that come to mind for a particular cue.



For example, when given the cue “tiger”, a person might produce the associates “animal”, “stripe”, and “bear”.

Are the clusters identified by Troyer et al. [1] reflected in this semantic network?

Let **S** be the matrix of similarities obtained by taking $s_{ij}=\exp\{-d_{ij}\}$, where d_{ij} is the length of the shortest path between animal nodes *i* and *j* in the semantic network. The similarity matrix according to additive clustering is **S=FWF′** where **F** is a feature matrix ($f_{ac}=1$ if animal *a* has feature *c*) and **W** is a diagonal matrix of (non-negative) cluster weights.



Visualizing the similarity between pairs of animals in our semantic network (darker colors represent stronger similarities):

(a) Similarity matrix obtained empirically from the semantic network.
(b) Similarity matrix obtained using the additive clustering model.

The two similarity matrices contain similar block structure, which supports the hypothesis that the clusters of animals are implicitly captured by the semantic network.

Random walks and semantic fluency

Random walks on semantic networks have previously been proposed as an account of behavior on fluency tasks: Griffiths et al. [4] showed that the prominence of words in human memory can be predicted by running the PageRank algorithm on a semantic network.

Does a random walk over a semantic network reproduce the optimal foraging phenomena identified by Hills et al. [2]? If so, this provides further support that the mechanism underlying memory search is a random walk.

Consider a Markov chain that starts at state X_0 = “animal”, and then at step *n* randomly generates the next state X_{n+1} according to a probability distribution that only depends on the current state X_n (and possibly the cue *C* = “animal”).

Transition model: can either be *uniform*, where the next state is chosen uniformly at random from the outgoing links of the current node, or *weighted*, where the probability of the next state is weighted according to the frequency of transitions in the word-association data [3].

Effect of cue at each step: can either be *non-jumping* (it has no effect except for initializing the chain at “animal”), or *jumping*, where the cue causes us to jump back to “animal” and transition from there, $P(X_{n+1}|X_n = \text{“animal”})$, with probability ρ (but otherwise transition normally with probability 1-ρ).

Formally, the space of models is defined by:

$$P(X_{n+1}|C = \text{“animal”}, X_n = x_n) = \rho P(X_{n+1}|X_n = \text{“animal”}) + (1-\rho)P(X_{n+1}|X_n = x_n)$$

where $P(X_{n+1}|X_n)$ is either *uniform* or *weighted*, and $\rho=0$ is *non-jumping* or $0 < \rho \leq 1$ is *jumping*. We define the inter-item retrieval time (IRT) between animal *k* and animal *k*-1 to be:

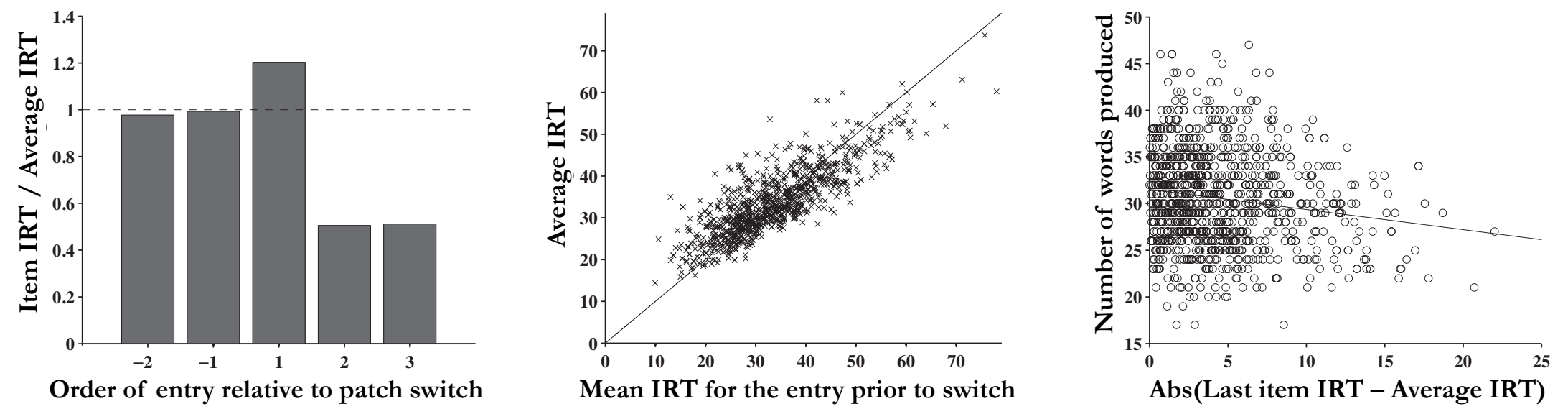
$$\mathrm{IRT}(k) = \tau(k) - \tau(k-1) + L(k)$$

where $\tau(k)$ is the first time animal *k* was seen on the random walk, and $L(k)$ is the length of the word for animal *k*.

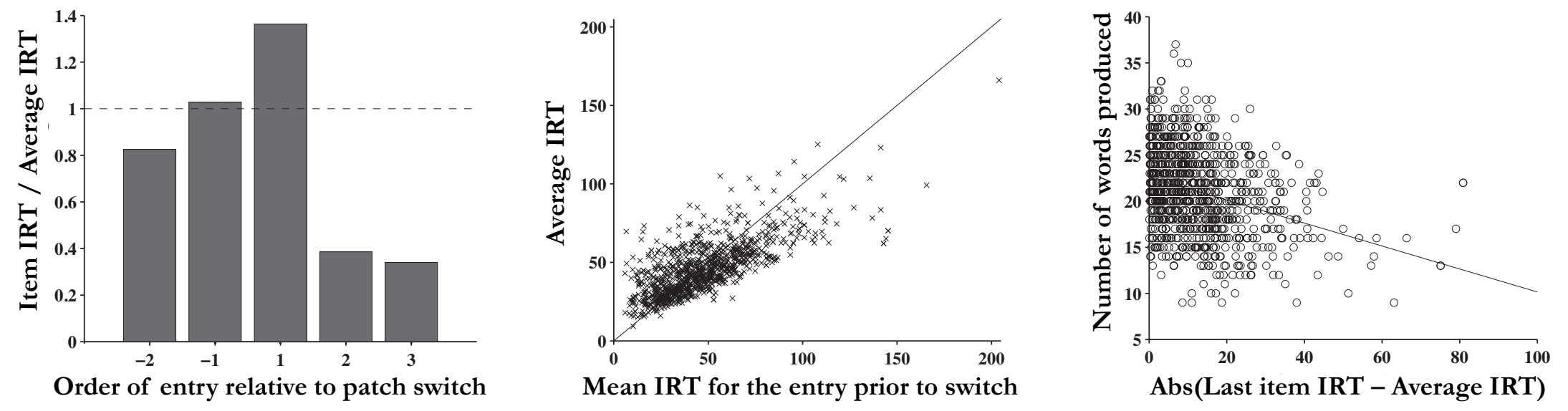
Model evaluation

Results averaged over 1000 simulations of each of the four random walk models run for a duration of 1750 iterations:

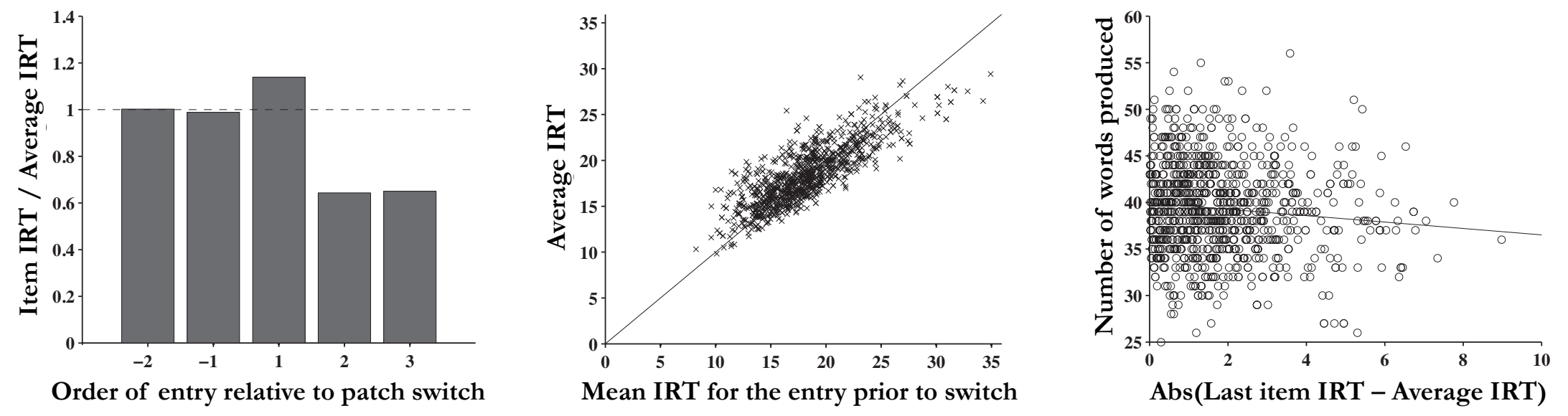
(a) Uniform transition model without jumps (ρ=0.00)



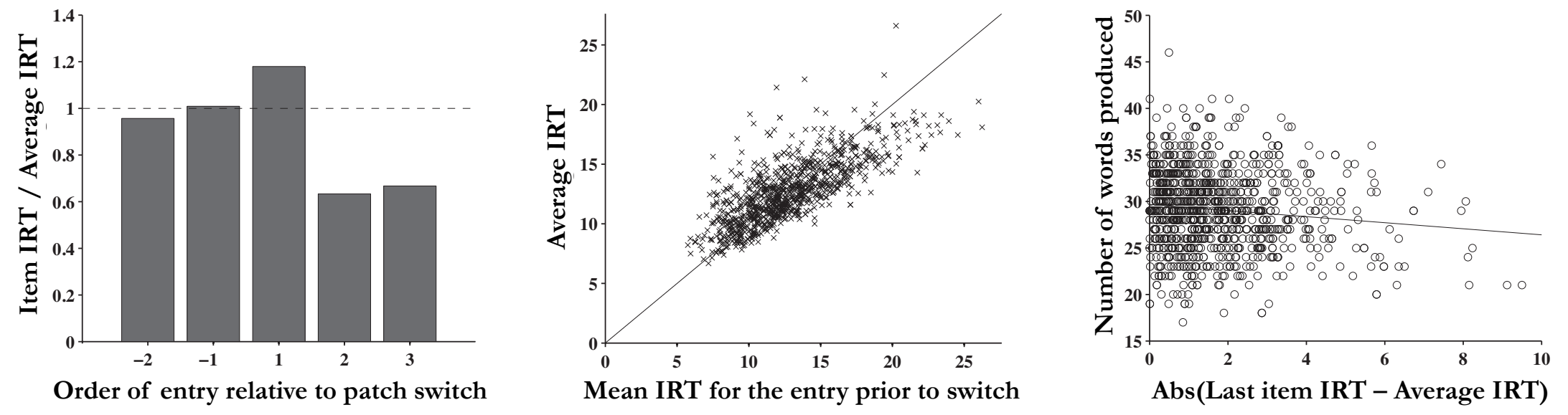
(b) Weighted transition model without jumps (ρ=0.00)



(c) Uniform transition model with jumps (ρ=0.05)



(d) Weighted transition model with jumps (ρ=0.05)



Subjected to the same analyses applied to human data, the same phenomena is seen across all four models. The first word starting a patch has the highest overall retrieval time, and the second word in a patch takes a significantly shorter amount of time. There is a strong correlation between pre-switch IRTs and average IRT, and a negative relationship between words produced and absolute difference of pre-switch and average IRTs.

These results demonstrate that behavior consistent with an optimal foraging policy can be produced by a simple undirected search process over a semantic network.

Discussion

A random walk on a semantic network exhibits similar complex behavior as participants in a semantic fluency experiment. Although human memory search can behave in a complex manner, it is not necessarily evidence that complex processes are producing the behavior.

Our result helps to clarify the possible mechanisms that could account for PageRank predicting the prominence of words in semantic memory [4], since PageRank is simply the stationary distribution of the Markov chain defined by this random walk.

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References:

[1] A.K. Troyer, M. Moscovitch, and G. Winocur. Clustering and switching as two components of verbal fluency: Evidence from younger and older healthy adults. *Neuropsychology*, 1997.
[2] T.T. Hills, M.N. Jones, and P.M. Todd. Optimal foraging in semantic memory. *Psychological Review*, 2012.
[3] D.L. Nelson, C.L. McEvoy, and T.A. Schreiber. The USF free association, rhyme, and word fragment norms. *Behavior Research Methods*, 2004.
[4] T.L. Griffiths, M. Steyvers, and A. Firl. Google and the mind. *Psychological Science*, 2007.