

Exploration and Exploitation in Memory Search Across the Lifespan

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Abstract

We used a formal model of memory (Raaijmakers & Shiffrin, 1981) to model semantic search processes of adults aged between 29 to 99 years of age in the animal naming task (“name all the animals you can”; Thurstone, 1938). Overall, our results support the idea that people switch between global frequency-based retrieval cues and local item-based retrieval cues to navigate their semantic memory. We extend this work by showing the involvement of an executive attention process, as switching is inversely correlated with digit span. Furthermore, our results reveal a further independent effect of aging, associated with increased switching between global and local memory cues for older individuals. These results are consistent with models of working memory and executive processing as representing a measure of goal perseverance and the ability to inhibit distracting information (Kane & Engle, 2004; Hills et al., 2010).

Keywords: search; semantic memory; modeling; aging.

Many real-world situations involve tradeoffs between known, currently available resources and other, more uncertain ones. In this paper, we argue that aging is associated with differences in dealing with this tradeoff in search from memory as a result of age-related cognitive decline. We draw our conclusions from results of formal modeling of memory search processes in a widely used and clinically relevant task: the animal naming task (“name all the animals you can”; Thurstone, 1938; Lezak, 1995). Our modeling approach is based on the dynamic component of Search of Associative Memory (Raaijmakers & Shiffrin, 1981) searching over a semantic representation of animals created using the semantic space model BEAGLE (Jones & Mewhort, 2004). This framework allows us to test competing formalizations of search in semantic space and, ultimately, link individual differences in semantic search to age and fluid intellectual abilities. Before describing the study, we first outline the motivation for studying the exploration-exploitation trade-off across the lifespan, and prior work on age differences in memory search.

The Exploration-Exploitation Dilemma

When searching for objects in space, such as when foraging for food, one has to trade off exploring new or less known regions and exploiting known ones, thus hoping to find the balance necessary to maximize the rate of return, a problem often called the exploration-exploitation dilemma.

Semantic retrieval can be understood as the search for desired information in cognitive memory space. As such, search in memory also requires handling an exploration-exploitation tradeoff as it involves a choice between exploiting a currently accessible area of a cognitive representation (i.e., local search) and exploring new areas (i.e., global search). Such a local-to-global search policy has been previously proposed for memory retrieval (Raaijmakers & Shiffrin, 1981; Troyer et al., 1997).

Hills, Todd, and Goldstone (2010) have proposed that a domain-general executive search process may underlie this local-to-global search behavior in both external and internal search tasks. There are several arguments supporting this view. First, there is evidence of cross-domain priming, such that experience with external search, such as a visual-spatial search task, primes internal search behavior in a lexical task (Hills, Todd, & Goldstone, 2008). Second, there are similarities in the strategies employed in external and internal search, with participants showing similar giving-up time strategies when searching for fish in virtual ponds (Hutchinson, Wilke, and Todd, 2008) and words from memory (Wilke, Hutchinson, Todd, & Czienskowski, 2009). Finally, there is evidence for domain-general neuromodulatory mechanisms involved in balancing the exploration-exploitation tradeoff (Cohen, McClure, Yu, 2007; Hills, 2006).

Given the proposed link between search processes and executive function more generally (Hills et al. 2010) and the posited role of catecholamines in modulating explorative behavior (Cohen, McClure, Yu, 2007; Hills, 2006), it is expected that age-related deficits in executive function caused by catecholaminergic deficits (Bäckman et al., 2000; Volkow, et al. 1998) could lead to significant differences in search behavior across the life span. Indeed, there is some evidence of age differences in dealing with exploration-exploitation tradeoffs, with aging leading to reduced exploration in external search (Louâpre, van Alphen, & Pierre, 2010; Mata, Wilke, & Czienskowski, 2009; Mata & Nunes. 2010). Also, there is a substantial amount of work showing significant age differences in memory retrieval (Spencer & Raz, 1995). More importantly, older adults tend to produce fewer words in semantic fluency tasks (e.g., Kozora & Cullum, 1995; Lanting, Haugrud, & Crossley, 2009; Tomer & Levin, 1993; Troyer, 2000), which could also be interpreted as reduced exploration in internal search,

or an earlier giving-up time. In the remainder of this paper we focus on age differences in semantic retrieval, and ask whether age differences in this domain can be attributed to the impact of aging on exploration-exploitation behavior.

Age Differences in Memory Search

The aging literature suggests that increased age is associated with memory retrieval deficits, namely, aging is associated with the production of fewer items in semantic retrieval tasks, such as the animal naming task (“name all the animals you can”; e.g., Kozora & Cullum, 1995; Lanting, Haugrud, & Crossley, 2009; Tomer & Levin, 1993; Troyer, 2000). The nature of the deficit or whether this is related to mastering the exploration-exploitation tradeoff, however, remains controversial.

One view holds that semantic retrieval deficits are simply due to general age-related slowing (Mayr, 2002; Mayr & Kliegl, 2000). According to this view, the nature of the processes underlying search are relatively constant across the life span but are executed at slower speeds with increased age. For example, Mayr and Kliegl (2000) found that younger and older adults showed similar switch-costs in terms of the time needed to produce items from two different categories.

An alternative perspective, the clustering-switching hypothesis, is that there are specific search processes that are impacted by aging (Troyer, Moscovitch, & Winocur, 1997). Troyer et al. have suggested that retrieving items from memory involves, first, a search for semantic categories, and second, a search for and production of words within a category. Accordingly, the search process can be described as exploration (i.e., switching between categories) and exploitation (i.e., clustering or producing items from within a category; see Gruenewald & Lockhead, 1980; Wixted & Rohrer, 1994; for similar views). Troyer et al. went on to analyze younger and older participant’s fluency productions and obtain a measure of switching (i.e., the number of switches between categories) and clustering (i.e., the mean number of items in a cluster). A few studies have now used this cluster-switching approach to investigate adult age-differences in semantic fluency and found that aging is associated with fewer switches between categories (Lanting, Haugrud, & Crossley, 2009; Troyer et al., 1997; Troyer, 2000; but see Rosseli, Tappen, Williams, Salvatierra, & Zoller, 2009). The results regarding the size of each cluster are less clear with two studies finding no differences (Troyer et al., 1997; Troyer, 2000), and others finding increased number of items per cluster with increased age (Lanting, Haugrud, & Crossley, 2009), at least for some semantic categories (Rosseli, Tappen, Williams, Salvatierra, & Zoller, 2009). Troyer and colleagues (Troyer et al., 2007; Troyer, 2000) have used this evidence to suggest that aging may be associated with difficulties in switching between categories, an ability linked to attentional and executive networks that are considerably affected by aging (Bäckman et al., 2000; Volkow, et al. 1998).

One difficulty facing these two approaches is their lack of

formalization, which goes hand-in-hand with underspecification of the source of age differences in semantic retrieval. For example, the speed account of retrieval deficits has not proposed what specific cues are used to access memory (Mayr, 2002). In turn, Troyer et al. (1997) proposed a detailed list of categories that are likely used to access semantic memory but have failed to specify how search is carried out within a category. Our work aims to fill this gap by testing how different mechanisms of search in the form of competing formal accounts best captures participants’ semantic retrieval. In particular, we utilize a new method for identifying local-to-global transitions, called the similarity drop model, which is based on a patch depletion model of memory (Hills, Todd, & Jones, 2008). In addition, we link individual differences in model parameters to age differences to assess the impact of aging on specific components of memory search.

Methods

Participants and Procedure

Two-hundred and one participants, with ages ranging from 27 to 99 (Median = 68, $M = 65.45$, $SD = 13.53$), participated in the study. Participants were recruited through postings at a health center in the San Francisco Bay Area as part of a study on health preferences (Carstensen, 2010). Participants completed a number of questionnaires regarding their health preferences followed by a small battery of cognitive tests, including the animal naming (Thurstone, 1938) and digit span (Wechsler, 1981) tasks which were included as measures of fluid intellectual ability. Participants were compensated for their participation in the study (\$50).

Representing the Structure of Semantic Memory

Beagle Semantic Space Model. We used the lexical semantic representations of animals computed in prior work (Hills, Todd, & Jones, 2008), using the BEAGLE model (Jones & Mewhort, 2007). BEAGLE learns semantic relations by assigning each word an *initial vector* with vector elements sampled randomly from a Gaussian distribution with $\mu = 0$ and $\sigma = 1/\sqrt{D}$ where D is the vector dimensionality (set to 1000 in these simulations). As the text corpus is processed, a word’s *memory vector* is updated each time the word is encountered as the sum of the initial vectors for the other words appearing in context with it. When the entire corpus has been learned, a word’s memory representation is then a vector pattern reflecting the word’s history of co-occurrence with other words. By this method, words that frequently co-occur will develop similar vector patterns (e.g., *bee-honey*), as will words that commonly occur in similar contexts, even if they never directly co-occur (e.g., *bee-wasp*). For all of our comparisons, the pairwise similarity metric used is the vector cosine (a normalized dot-product between two word vectors). BEAGLE was trained on a subset of Wikipedia, composed of approximately 400 million word tokens and 3 million word types. Support for BEAGLE comes from its considerable success at accounting for a variety of human

semantic data including semantic typicality, categorization, and sentence completion (Jones & Mewhort, 2007), as well as for a range of semantic priming data (Jones, Kintsch, & Mewhort, 2006).

The Troyer et al. (1997) categorization. The Troyer et al. (1997; see also Troyer, 2000) categorization contains 22 non-exclusive categories, including “African animals”, “water animals”, and “beasts of burden.” The categorization contained 155 unique animal names, but was extended by Hills, Todd, & Jones (2008) to contain an additional 214 animal names found in Wikipedia. These were categorized according to the original 22 categories found in Troyer et al. (1997), based on the descriptions of the additional animals found in Wikipedia. Because this coding does not change Troyer et al.’s coding, the new coding is fully compatible with previous results using the Troyer et al. categorization scheme.

Modeling Search in Semantic Memory

Memory retrieval can be viewed as the result of probing a cognitive representation with one or more cues to activate a memory response (e.g., Gronlund & Shiffrin, 1986; Walker & Kintsch, 1984). Under this assumption, the simplest possible model would assume that search is guided by a single cue. More complex models could assume that participants use a combination of cues, or even dynamically switch between cues as a function of retrieval success. To model these various approaches we used a model framework similar to the item-level recall probability equation from SAM (see Raaijmakers & Shiffrin, 1981):

$$P(I_i | Q_1, Q_2, \dots, Q_k) = \frac{\prod_{k=1}^M S(Q_k, I_i)^{w_k}}{\sum_{j=1}^N \prod_{k=1}^M S(Q_k, I_j)^{w_k}} \quad (1)$$

where $S(Q_k, I_i)$ represents the retrieval strength from cue Q_k to item I_i in memory. w_k represents the saliency or attention directed at the k th cue. Two cue categories were considered: a global context cue and a local cue representing the most recently recalled item. The context cue amounts to the global strength of each item in the category of “animals that you know”, and represents the cue for *global search*; we assume that this is best approximated by a retrieval structure based on the frequency of occurrence of each animal name in the Wikipedia corpus. The cue representing the most recently recalled item represents the cue for *local search*. For local search, we assume a retrieval structure that is determined by the pairwise semantic similarities produced by BEAGLE. Note that each of the retrieval structures (representing either frequency or semantic similarity) is a matrix providing the retrieval strength for each possible cue with all possible animals that could be produced. Thus, given a set of cues and a set of retrieval structures, we can compute the predicted retrieval probability for any sequence of animal names.

Using this framework, we tested several static and dynamic models that differed in terms of the retrieval

structures and cue dynamics used to represent the search process. Static models use a single cue arrangement over the entire production interval (e.g., always using the global context represented by frequency).

Dynamic models, by contrast, transition between local and global cues, using the local semantic similarity retrieval structures within a cluster¹ and using the global frequency-based retrieval structure between clusters. In the case of the Troyer et al. (1997) defined category transitions, transitions from a local to a global cue representation occur whenever one item is not in the same category as the previous item. In the case of similarity drop transitions, transitions are identified wherever a sequence of four items, A, B, C, D have BEAGLE-defined semantic similarities that follow the pattern $S(A,B) > S(B,C)$, and $S(B,C) < S(C,D)$, i.e., where the similarity drops between clusters. In previous work, we identified these similarity drops as places where individuals left a patch of locally semantically similar items to transition globally to another patch of locally semantically similar items (Hills, Todd & Jones, 2008). Once an item was recalled, that item was removed from the retrieval structure. For each model, the sensitivity parameter for the k th representation, w_k , was fit separately to each participant using the maximum likelihood method.

Results

Participants produced on average 17.0 ($SD = 5.35$; range 5 - 33) animal names. As found in previous work (e.g., Troyer et al., 1997), increased age was associated with producing significantly fewer items ($B = -0.12$, $t(199) = -4.83$, $p < .001$). Mean digit span was 16.68 ($SD = 4.38$), which was also negatively correlated with age ($B = -0.06$, $t(198) = -2.53$, $p = 0.01$).

Results of Modeling Semantic Memory

Table 1 presents the median improvement over a random model in the Bayesian Information Criterion (ΔBIC) as well as the median w . The random model assumes that all remaining items in the social network have an equal chance to be recalled. Note that the static and dynamic models are not strictly comparable as in order to identify transition points the dynamic models use information from the data about the to-be-retrieved items. Nonetheless, the dynamic models should outperform the static models, if transition points are accurately identified.

Results show that the best single predictor of recoveries is frequency, with high frequency items being more likely to be produced than lower frequency items. Combining both global and local information was an improvement over one-cue models. Adding dynamic local-to-global transitions based on the similarity drop model further improved the model fit. Surprisingly, the addition of dynamic local-to-global transitions based on the Troyer et al. (1997)

¹ The local search combines both local and global cues, as in Raaijmakers & Shiffrin (1981).

categorization scheme did not perform as well as the static model using the same retrieval structures.

Table 1. Median improvement in BIC relative to a random model. Models were fit using the maximum likelihood method to find the optimal w (medians reported) for each cue-retrieval structure combination, for each individual. The + indicates the product of the retrieval strengths was computed in Equation 1 for the local memory search.

| | Retrieval structures | Δ BIC | w |
|-------------------------------------|----------------------|--------------|------|
| <i>Single-cue</i> | | | |
| | Frequency | 19.45 | 2.22 |
| | Semantic similarity | 15.47 | 1.33 |
| <i>Multi-cue</i> | | | |
| | Frequency + | 23.75 | 1.79 |
| | Semantic similarity | | 1.06 |
| <i>Dynamic cues</i> | | | |
| <i>-Troyer et al. transitions</i> | | | |
| | Frequency + | 22.97 | 2.08 |
| | Semantic similarity | | 1.49 |
| <i>-Similarity drop transitions</i> | | | |
| | Frequency + | 24.51 | 1.88 |
| | Semantic similarity | | 1.31 |

Switches from BEAGLE similarity drop and Troyer et al are significantly correlated with one another, (Pearson's correlation coefficient = 0.61, $t(199)=10.99$, $p < 0.001$). There are a mean of 5.14 similarity drop switches per item, and a mean of 9.24 Troyer et al. switches (paired-t-test, $t(200)=-23.63$, $p < 0.001$).

Overall, these results are supportive of a dynamic process, in which people dynamically switch between global (frequency) and local (item) cues to search memory. The location of transition points was, however, better predicted by the similarity drop model than it was by a model using the transitions proposed by Troyer et al. (1997).

Is Dynamic Switching Correlated with Age?

Both the absolute number of Troyer et al. (1997) switches and the BEAGLE-defined similarity drop switches are correlated with age (first column in Table 2), with older individuals switching less often in absolute number than younger individuals. However, the number of switches is strongly correlated with the total number of productions (for Troyer et al. (1997) switches: Pearson's correlation coefficient = 0.74, $t(199) = 15.60$, $p < .001$; Similarity drop switches: Pearson's correlation coefficient = 0.88, $t(199) = 26.31$, $p < .001$). This produces an obvious confound, as switches may occur at regular intervals during production,

and thus may not represent a second search component as proposed by Troyer et al. (1997), but simply the outcome of a single slower production rate, consistent with Mayr (2002).

A potentially more meaningful correlation with age is to look at the number of switches/item. These are weakly correlated with total number of productions (for similarity drop switches, Pearson's product-moment correlation = -0.17, $t(199)=-2.50$, $p < 0.05$; for Troyer et al switches, Pearson's product moment-correlation = -0.21, $t(199)=-3.07$, $p < 0.01$). A negative correlation indicates that more productions are associated with fewer switches per item, which may indicate that participants who produce more items do so by producing items that are, on average, more similar to one another.

Table 2: Correlation between age and switching

| | Switches | Switches/Item |
|-----------------|----------|---------------|
| Similarity drop | -0.23*** | 0.19** |
| Troyer et al. | -0.34*** | -0.10 |

The second column in Table 2 shows that switches-per-item is positively correlated with age for the similarity drop switches, but not for the Troyer et al. switches. Figure 1 shows the switches per item for younger and older groups using a median split (*Median* = 68), with fewer switches per item for younger versus older individuals ($t(199) = -2.67$, $p < .01$). This is inconsistent with the Troyer et al. account of switching, which suggests that older adults switch less often between representations, but as argued below is consistent with an account that assumes increased switching is associated with executive deficits.

Is Dynamic Switching Correlated with Individual Differences in Executive Processing?

One alternative view to Troyer et al.'s (1997) proposition that age-related executive deficits lead to reduced switching between representations is that the use of local cues in memory retrieval is a demanding process that involves focusing attention on item-level information and/or inhibiting global information. Accordingly, executive and attentional deficits could lead to a significant increase in switching between the use of a default global cue and the cognitively demanding use of local, item-based ones. As a consequence, the effect of age should be similar or amount to the effect of reduced cognitive abilities, such that reduced fluid abilities lead to increased switching between global and local memory cues. A multiple regression predicting similarity drop switches per item results in a significant effect for both digit span ($B = -0.002$, $t(197)=-2.42$, $p = 0.02$) and age ($B = 0.0006$, $t(197) = 2.27$, $p = 0.02$). Figure 2 shows the regression line for digit span on switches per item. That is, individuals with higher digit spans have fewer switches per item; younger individuals also have fewer switches per item. Moreover, the effect of age remains significant even after controlling for the effect of digit span,

indicating that digit span and age represent at least partially independent variables in predicting the dynamics of the memory search process based on similarity drop.

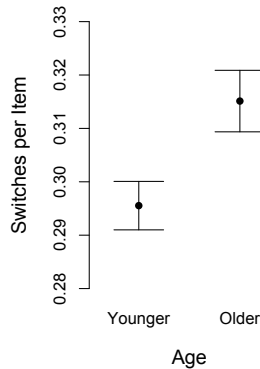


Figure 1. Switches per item based on the similarity drop model for younger and older individuals, based on a median split of age (*Median* = 68).

Discussion

The current work attempted to contribute to our understanding of adult development changes in semantic search. We used a formal model of memory (Raaijmakers & Shiffrin, 1981) to model semantic search processes of adults aged between 29 to 99 years of age in the animal naming task (“name all the animals you can”; Thurstone, 1938). Overall, our results support the idea that people transition between local and global cues when searching long-term memory. Specifically, our model searching over a semantic representation based on BEAGLE (Jones & Mewhort, 2004) provides a plausible account of search in memory in this task and, further, is consistent with previous work suggesting that people switch between global frequency-based retrieval cues and local item-based retrieval cues to navigate their semantic memory (e.g., Raaijmakers & Shiffrin, 1981; Gruenewald & Lockhead, 1980).

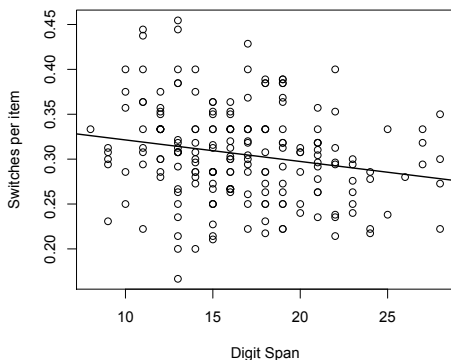


Figure 2. The relationship between digit span and switches per item based on the similarity drop model.

Our results also make a contribution to the debate concerning the source of age differences in fluency tasks. Our results contradict the view that semantic retrieval

deficits are confined to slower production rates due to general age-related slowing (Mayr, 2002; Mayr & Kliegl, 2000) because we find links between age and the pattern of cue use in dynamic search from memory. The results also go beyond the idea that age-related cognitive decline in executive function (Bäckman et al., 2000; Volkow, et al. 1998) is associated with *decreased switching between representations* when searching for items in semantic space (Troyer, Moscovitch, & Winocur, 1997). We do replicate the finding that age is negatively correlated with the total number of switches between categories. However, this measure may be a poor indicator of dynamic search processes because it is strongly correlated with the total number of productions.

More interestingly, our modeling results suggest that age-related cognitive decline is associated with *increased switching between memory cues*. Our results show that the number of switches between global and local cues per item produced increased with age. The number of switches between global and local cues per item produced was also correlated with a measure of digit span—with more switching correlated with lower spans. This is consistent with prior models of working memory and executive processing as representing a measure of the ability to inhibit distracting information (Kane & Engle, 2004).

The perspective of an executive search process that directs search may help reinterpret some previous findings in the field of aging. If executive processing represents the ability to focus on a specific subgoal, then aging and/or reduced cognitive ability would lead to a greater likelihood of switching between subgoals, or terminating search processes. According to this view, previous work showing less information search in older adults (Louâpre, van Alphen, & Pierre, 2010; Mata, Wilke, & Czienskowski, 2009; Mata & Nunes, 2010) could be interpreted as resulting from greater switching between subgoals in a hierarchical subgoal process, leading to earlier termination of the search (Hills et al., 2010). Thus, exploration is potentially a confusing term because it confounds the time spent searching and the pattern of search. While the time spent searching represents persistence on one goal (i.e., searching), switching between areas of local processing represents switching between subgoals—i.e., earlier subgoal abandonment—and thus lack of persistence. We hope that the use of detailed and formal models like the one proposed here will help shed light on these issues and provide new insights into how aging impacts exploration in memory search.

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