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How Healthy Aging and Dementia Impact Memory Search

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Abstract

We model the semantic recall sequences of 424 older adults aged between 69 to 103 years in the animal fluency task. Our results suggest that, under normal intellectual functioning, memory search in old age (69–84 years) is consistent with a dynamic process that switches between retrieval probes. With dementia and very old age (85–103 years), however, memory search seems to become more consistent with a static process that activates items in memory as a function of their frequency. The weight that probes have in determining the activation of items in memory seems to be an informative signature of the impact of healthy aging and dementia on memory search. Our results show that, with healthy aging and dementia, the activation of items in memory is increasingly more determined by the frequency of past experience with those items.

Keywords: Search; semantic memory; modeling; aging.

Introduction

Ronald Reagan became the oldest president elected in American history, when he took office at age 69, in 1981. He was diagnosed with Alzheimer's in 1993, the most common form of dementia, four years after he left office. Yet Reagan's signs of memory decline while in office – like forgetting names and being at a loss for words – have led to much speculation about how early dementia had set in. The question was whether his memory slips were a sign of normal aging or rather the early symptoms of dementia.

Studies using the animal fluency task (“name all the animals you can think of”; Thurstone, 1938) have shown that healthy older adults recall fewer items relative to younger adults within a limited time interval (e.g., Hills, Mata, Wilke, & Samanez-Larkin, 2013; Kozora & Cullum, 1995), in much the same way as older adults with dementia produce fewer items compared with healthy older adults (e.g., Beatty, Salmon, Testa, Hanisch, & Troster, 2000; Epker, Lacritz, & Cullum, 1999). In this paper, we examine how healthy aging and dementia impact search in semantic memory beyond the sheer reduction in the number of recalls. To this end, we formally model the recall sequences of 424 older adults aged between 69 to 103 years in the animal fluency task. We then examine individual differences in model fit and parameter estimates, as a way of identifying signatures of cognitive decline in memory search with healthy aging and dementia.

Static and Dynamic Search in Semantic Memory

Memory retrieval can be viewed as the result of probing a memory representation with one or more probes to activate a response (e.g., Gronlund & Shiffrin, 1986; Walker &

Kintsch, 1985). We apply two classes of models based on prior work – static *vs.* dynamic – that make different assumptions about how retrieval probes are used to search memory in the fluency task (Hills et al., 2013). Consider the following two types of probes. One type of probe, the frequency probe, activates animal names in memory as a function of their frequency of past occurrence. A second type of probe, the similarity probe, activates each item in relation to its semantic similarity to the previously-recalled item. In a static model, search is guided by the same probe arrangement over the entire recall interval (i.e., by either probe alone or by a combination of the two). A dynamic model, on the contrary, switches between a frequency probe and a probe that combines frequency and similarity to traverse clusters of similar items in memory. When leaving a cluster, a dynamic model uses frequency alone to find a new cluster, and goes back to using a combination of frequency and similarity information as the new cluster is entered. Past work has found that, from early to late adulthood, search in memory is overall more consistent with a dynamic search model than with a static model that uses the same probe arrangement during the entire recall sequence (Hills et al., 2013).

In this paper, we examine the relative fit of static and dynamic models in old and very old age, for healthy individuals and individuals diagnosed with dementia. In very old age, do people use memory retrieval probes more in accordance with a dynamic model than with a static model as younger cohorts do? Moreover, we test alternative mechanisms of decline in memory search by investigating individual differences in the use of retrieval probes. We next turn to a brief discussion of the alternative mechanisms of decline in memory search.

Mechanisms of Decline in Memory Search

Existing hypotheses proposed to account for age-related differences in the number of items produced in fluency tasks make different assumptions about how memory search declines with aging. The *age invariance hypothesis* proposes that aging is associated with unaffected semantic processing, and thus predicts no age differences in the use of retrieval probes (Mayr & Kliegl, 2000). Two alternative hypotheses argue that the impact of aging affects the ability to switch between probes. The *cluster-switching hypothesis* views memory retrieval as a dynamic process involving a search for semantic categories like “pets”, and a search for words within a category (e.g., “dog”) (Troyer, Moscovitch, & Winocur, 1997; Troyer, 2000). A common finding is that aging is associated with fewer total switches between categories, leading to the proposal that aging is associated

with reduced switching between retrieval probes (categories) (Troyer et al., 1997; Troyer, 2000). On the other hand, the *cue-maintenance hypothesis* (Hills et al., 2013) derives from studies showing that aging is associated with lower working memory capacity, defined as the ability to keep focus on one probe while ignoring distracting ones (e.g., Bopp & Verhaghen, 2007). Age-related decline in working memory capacity should lead to a loss of probe focus, and therefore to increased switching between probes (e.g., Unsworth & Engle, 2007). Existing evidence suggests that, from early to late adulthood, age is associated with an increase in switching between probes, per item recalled, in support of the cue-maintenance hypothesis of decline in memory search (Hills et al., 2013).

We examine which mechanism of decline best describes individual differences in switching in old (69–84 years) and very old age (85–103 years), between healthy individuals and individuals diagnosed with dementia. These mechanisms of decline, which have been proposed to account for age-related differences in fluency performance, can be used to test additional alternative hypotheses regarding memory decline in dementia. One hypothesis holds that memory impairment in dementia results from the acceleration of the same mechanism that leads to memory decline in healthy aging (e.g., Brayne & Calloway, 1988; Huppert, 1994; Huppert & Brayne, 1994). On this view, age-related differences in switching among individuals diagnosed with dementia should mirror age-related differences in healthy individuals. According to an alternative framework, however, memory decline in healthy individuals and in individuals with dementia is the product of distinct processes that target different brain systems (e.g., Albert, 1997; Gabrieli, 1996). This framework thus suggests that age-related differences in switching should arise from distinct decline mechanisms in healthy aging and dementia.

To summarize, we examine whether semantic search in healthy old age and dementia is more consistent with a static or with a dynamic model. Moreover, we test different mechanisms of decline in memory search by investigating individual differences in model fit and parameter estimates.

Methods

Participants and Procedure

The present work uses data from the Berlin Aging Study, a longitudinal study on aging (Baltes & Mayer, 1999). Specifically, we analyze the animal fluency data that was collected in the first measurement occasion of the study, between 1990 and 1993. In the animal fluency task, participants were asked to respond verbally to the probe “Name all the animals you can think of” within 90 seconds, with their responses being tape-recorded. We retrieved participants’ retrieval sequences from the tapes that were still functional, having compiled the responses of 424 individuals, with ages ranging from 69 to 103 (mean = 84.77, $SD = 8.58$). Of these 424 individuals, 91 were diagnosed with dementia (mean age = 90.31, $SD = 6.53$)

according to the guidelines of DSM-III-R, and 333 individuals (mean age = 83.25, $SD = 8.45$) were considered to have normal intellectual functioning.

The Representation of Semantic Memory

The first step towards formalizing search in semantic memory is to provide an explicit representation of the space being searched. We used the semantic representations of animals computed in prior work (Hills, Jones, & Todd, 2012) using the BEAGLE semantic space model (Jones & Mewhort, 2007). The BEAGLE model was trained on a subset of Wikipedia, composed of approximately 400 million word tokens and 3 million word types. Once the entire corpus has been learned (see Hills et al., 2012, for a description of the learning process), a word’s memory representation is a vector pattern reflecting the word’s history of co-occurrence with other words. Words that frequently co-occur end up developing similar vector patterns (e.g., *bee-honey*), as do words that commonly occur in similar contexts, even if they never directly co-occur (e.g., *bee-wasp*). Based on the representation learned by BEAGLE, we used the frequency of occurrence of each animal name in the Wikipedia corpus as well as the pairwise cosine similarities between animal names for our comparisons.

Alternative Models of Semantic Search

To describe memory retrieval given this well-defined memory representation, we used a model framework similar to the item-level recall probability equation from the Search of Associative Memory model (SAM; Raaijmakers & Shiffrin, 1981):

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

where $S(Q_k, I_i)$ represents the retrieval strength from probe Q_k to item I_i in memory, and w_k represents the saliency or attention directed at the k^{th} probe. The probability of retrieving a given item, I_i , is given by the ratio of the activation strength of that item and the sum of the activation of all other items in memory given those same probes. Finally, β is a free parameter that indicates how strongly the person’s recall was determined by the probe; higher values of β lead items with higher retrieval strengths for a given probe, Q_k , to gain a larger share of the recall probability, while lower values of β distribute the probability of recall more evenly over all items.

We considered the *frequency* probe and the *similarity* probe introduced earlier in the paper. The *frequency* probe activates each item in memory as a function of the frequency of occurrence of each animal name in the Wikipedia corpus. The *similarity* probe activates each item in memory in relation to its semantic similarity to the

previous item recalled. Thus, the most recently recalled item is the probe used to query memory, and activation is defined as the pairwise semantic similarities produced by BEAGLE with all animals yet to be recalled. Given a particular probe arrangement, we can compute the predicted retrieval probability for any sequence of animal names by repeatedly using Equation 1. The β parameters were fit to each participant's data to maximize the observed recall probabilities and produce a maximum likelihood fit.

We tested four models differing in the nature of probe use. All models share the assumption that the probability that an item is the first item recalled is a function of its frequency. From the second recall onwards, the models differ in whether they use frequency and similarity information in a static or dynamic way. Static models use the same probe arrangement over the recall interval. The *static frequency model* uses a single probe: frequency. This assumes that individuals' recall sequences of animals reproduce their natural strength of activation in memory as a consequence of frequency alone. The *static similarity model* also uses a single probe: semantic similarity. This assumes that individuals rely only on the previously recalled item as a probe for the next recall, producing a chain of pairwise associated animals. The *static combined model* represents the simultaneous combination of frequency and semantic similarity. This assumes a process based on semantic similarity to the previous item that is further informed by the frequency of past experience with those items.

The *dynamic model* switches between a frequency probe and a probe that combines frequency and similarity to traverse clusters of similar items in memory. When leaving a cluster, a dynamic model uses frequency alone to find a new cluster, and goes back to using a simultaneous combination of frequency and similarity information as the new cluster is entered. Transitions are predicted by the model only after they occur, meaning that the model tests where the most plausible locations for transitions are, given the underlying representation. The model switches between retrieval probes wherever a sequence of items A, B, C, D have semantic similarities that follow the pattern $S(A,B) > S(B,C)$, and $S(B,C) < S(C,D)$. That is, similarity drops between clusters and then increases again once search resumes with a new cluster (e.g., the sequence DOG, CAT, SHARK, WHALE would have two clusters, divided by a similarity drop between CAT and SHARK).

In our data, healthy aging and dementia are associated with an increase in the proportion of items repeated. For this reason, and in contrast to previous studies (Hills et al., 2012, 2013; Hills & Pachur, 2012), we did not exclude repetitions from participants' retrieval sequences, nor did we remove items from the memory representation after they were recalled. Although the current models do not distinguish new responses from repeated ones when calculating the retrieval probabilities, we are currently developing a generalized version of the models that takes into account how likely participants are to repeat previous responses.

Results and Discussion

Figure 1 shows the mean number of correct responses produced in old and very old age, for healthy individuals and individuals diagnosed with dementia, calculated after excluding repeated items. Throughout our analyses, the group "old age" includes participants with ages between 69 and 84 years, and the group "very old age" includes participants with ages between 85 and 103 years. As expected, age was associated with recalling fewer items ($t(422) = -11.32, p < .001, r = -.48$). The mean number of correct responses produced decreased with age, both for healthy individuals and individuals with dementia. In addition, individuals with dementia produced fewer correct responses relative to individuals without dementia ($t(422) = -12.03, p < .001, r_{pb} = -.51$). These results indicate that both healthy aging and dementia are associated with a decline in the number of items retrieved from memory. In what follows, we present our results for the modeling of semantic retrieval in old and very old age.

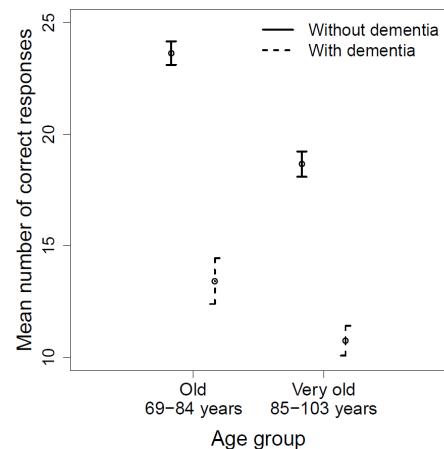


Figure 1: Mean number of correct responses produced in each group. Error bars represent the standard error of the mean.

Do people switch between retrieval probes in old and very old age to navigate their semantic memory?

Table 1 presents the Bayesian Information Criterion (BIC) of the four models. BIC is a commonly used measure to compare the fit of different models while penalizing them for the total number of free parameters that they have, as a way of reducing overfitting (Lewandowsky & Farrell, 2011). Whereas the static single-probe models have only one free parameter, the models that use both frequency and similarity have two free parameters, each indicating how strongly the person's recall was determined by each type of information. Note that smaller values of BIC indicate a better model fit. Also, due to differences in the number of items recalled, the BIC values for the different models are only informative if compared within groups.

Table 1: Median Bayesian Information Criterion (BIC) of static and dynamic models per group.

Models	Without dementia		With Dementia	
	Old (69-84)	Very old (85-103)	Old (69-84)	Very old (85-103)
<i>Static</i>				
Frequency	293.34 (95.48)	223.51 (92.39)	163.27 (56.7)	149.46 (79.75)
Similarity	321.69 (106.49)	262.5 (101.99)	180.73 (61.94)	182.68 (95.46)
Combined	285.72 (95.83)	226.60 (92.30)	164.07 (54.19)	147.49 (79.62)
<i>Dynamic</i>				
	278.08 (95.69)	226.60 (92.33)	162.19 (54.68)	146.46 (79.68)

Note. Standard deviations are shown in parentheses.

The static, frequency model fit the data of all four groups better relative to the static, similarity model, suggesting that the best single predictor of recall was frequency rather than similarity. The pattern of results is, however, mixed across groups with respect to the fit of the models that use both frequency and similarity. The recall sequences of healthy individuals aged between 69-84 years were better fit by the static, combined model than by the two static single-probe models. Moreover, the model that incorporates dynamic transitions between probe arrangements outperformed the static combined model, being therefore the best fitting model for healthy individuals aged between 69-84 years. This finding is in line with past work showing that younger cohorts search memory according to a dynamic process that switches between a frequency probe and a probe that integrates frequency and similarity (Hills et al., 2013).

For the other groups of participants, however, the results show smaller differences in BIC between the static model that relies exclusively on frequency information and more complex models that use both frequency and similarity in a static or dynamic fashion. This suggests that the static frequency model may give a comparatively better account of memory search in very old age and dementia than for the healthy younger cohort. Yet the smaller BIC differences between models indicate that it is difficult to distinguish between them in very old age and dementia, thus calling for other methods to address the model selection problem.

How do healthy aging and dementia impact memory search?

The number of switches per item was essentially unrelated to the total number of items recalled ($t(422) = -1.21$, $p = .22$, $r = -.06$). Additionally, it was also not related with age ($t(422) = -1.05$, $p = .29$, $r = -.05$), or with the presence of dementia ($t(422) = .87$, $p = .38$, $r_{pb} = .04$). Contrary to the cluster-switching and the cue-maintenance hypotheses, both of which posit specific changes in switching with increased age, these results seem to suggest that there are no differences in the nature of probe utilization with increased age, in support of the age invariance hypothesis. This result

is not consistent with the age-related increase in switching found in previous work for a younger cohort (Hills et al., 2013), suggesting that different mechanisms of decline may be at play in adulthood and later in life. Additionally, the finding that dementia was, as for healthy aging, unrelated with switching suggests that the decline of memory search in dementia may result from the acceleration of the same mechanism that leads to decline in healthy aging.

We believe, however, that there is an alternative, more sensible interpretation of these findings. As seen above, as people age, a static model appears to be better supported relative to a dynamic model. Thus, the number of switches per item recalled may not be an appropriate signature of the impact of very old age and dementia on memory search. A more informative signature of the decline of memory search in old age may be given by the free parameter, β , which provides a measure of the deterministic nature of the activation given a specific retrieval probe. Different cohorts of healthy older adults and older adults with dementia may search memory in different ways, and these may influence the estimates of the β parameter. Higher values of β for the frequency probe lead very frequent items to have a larger share of the recall probability. Likewise, higher values of β for the similarity probe give a larger share of the recall probability to items that are very similar to the previously-recalled item. Lower values of β distribute the recall probabilities more evenly over all items in memory. Individual differences in the estimates of the β parameter may thus suggest alternative mechanisms of decline of memory search, whereby memory probes are given different weights in determining the recall probabilities.

Figure 2 plots the mean estimates per group for the β parameters corresponding to the frequency probe (panel A) and the similarity probe (panel B) in the static, combined model. Note that the parameter estimates are not comparable between probes due to the different scales of the Wikipedia-defined frequencies and semantic similarities.

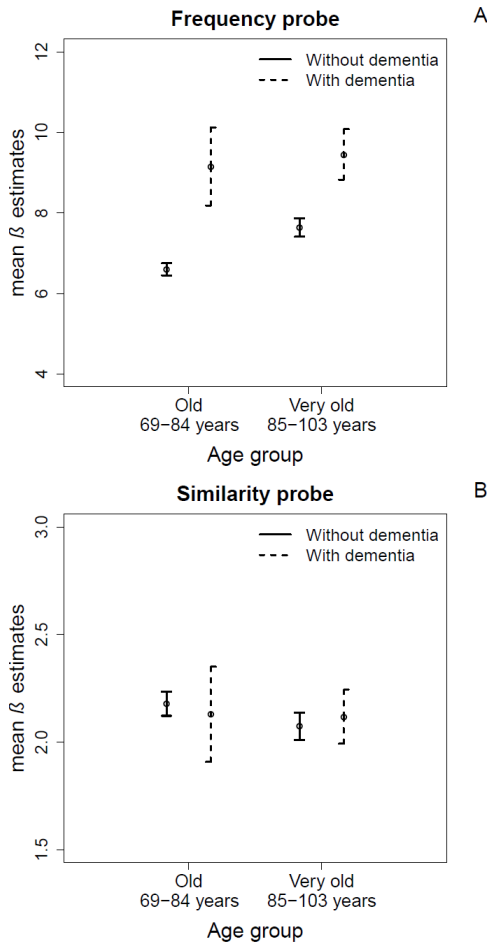


Figure 2: Mean estimates per group for the β parameters corresponding to the frequency probe (A) and similarity probe (B) in the combined static model. Error bars represent the standard error of the mean.

Figure 2 shows that, for individuals with normal intellectual functioning, there was an age-related increase in the estimates for the frequency probe, and a decrease in the estimates for the similarity probe. This indicates that memory search is more strongly determined by item frequency in very old age, but the weight of semantic similarity seems to decrease. For individuals diagnosed with dementia, the results demonstrate that there are no age differences in the estimates for either retrieval probe. However, the results suggest an association, independent of age, between dementia and the increasing weight of item frequency in determining the probability of recall.

This increase in the saliency of the frequency probe may be related to the observed increase in the proportion of repeated items with age ($t(422) = 6.07, p < .001, r = .28$) and dementia ($t(422) = 8.04, p < .001, r_{pb} = .36$). Figure 3 shows the mean of the log-transformed Wikipedia-defined frequencies for newly occurring items and repeated items produced as a function of age (panel A) and dementia diagnosis (panel B). Error bars represent the standard error of the mean.

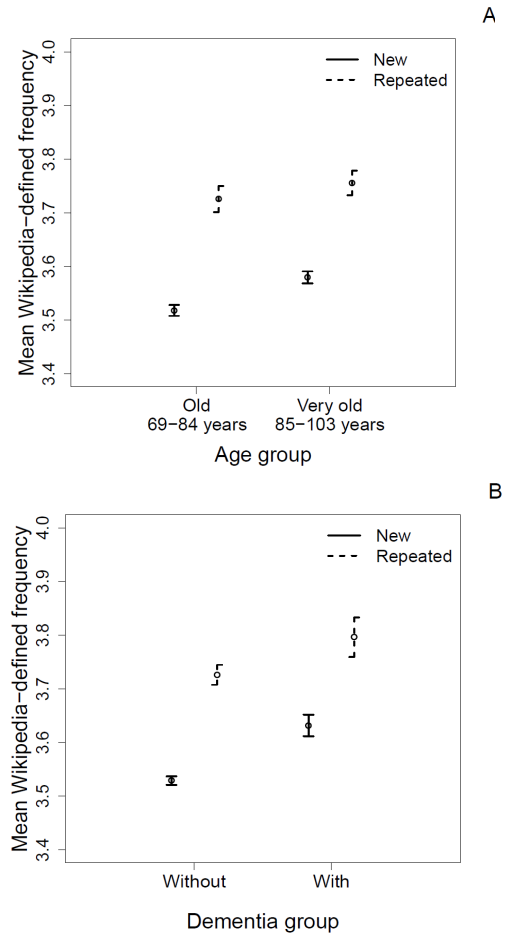


Figure 3: Mean Wikipedia-defined frequencies for new and repeated items produced as a function of age (A) and dementia diagnosis (B). Error bars represent the standard error of the mean.

In both age and dementia groups, repeated items had overall higher frequencies when compared with items recalled for the first time. Moreover, both age and dementia were associated with an increase in the Wikipedia-defined frequencies of the items repeated and, especially, of newly occurring items. Further modeling efforts are required to explore the contribution of repetitions to the higher saliency of the frequency probe in very old age and dementia.

Conclusion

Our results suggest that, in the absence of dementia, memory search in early old age is consistent with a dynamic process that switches between a frequency probe and a probe that integrates frequency and similarity to traverse clusters of items grouped in memory by semantic similarity. This finding is in line with past work showing that younger cohorts search memory according to a dynamic process (Hills et al., 2013). However, in very old age and dementia, memory search processes appear to become more static, relying more on frequency to probe memory.

Our results further show that the proportion of switches between probe arrangements is unrelated with age and with the presence of dementia for older individuals. This result is in contrast with findings from previous studies showing that younger cohorts switch more often between probes with increasing age (Hills et al. 2013), thus suggesting that different mechanisms of decline may be at play in adulthood and later in life. Yet the saliency of memory retrieval probes may be a more informative signature of the impact of very old age and dementia on memory search. We have shown that, with healthy aging and dementia, the activation of items in memory is increasingly determined by the frequency of past experiences with those items. This result is consistent with the finding above that, in very old age and dementia, memory search appears to become more consistent with a static process that uses frequency to probe memory. Finally, the increase in the saliency of the frequency probe seems to be related with the increase in the number of repetitions. While age is associated with an increase in the number of repetitions, the items people repeat have a higher frequency of past occurrence compared with items recalled for the first time.

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