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COMMENT

Aging and Associative Recognition: A View From the DRYAD Model of Age-Related Memory Deficits

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How do we best characterize the memory deficits that accompany aging? A popular hypothesis, articulated originally by Naveh-Benjamin (2000) and reviewed in the accompanying article by Smyth and Naveh-Benjamin (2016), suggests that older adults are selectively deficient in establishing *associations* between to-be-learned memoranda and as a result have deficits in memory for sources or contexts. An alternative proposal, called *density of representations yields age-related deficits* (DRYAD) and outlined in recent articles by Benjamin (2010) and colleagues (Benjamin, Diaz, Matzen, & Johnson, 2012), attributes disproportionate deficits in memory to a global, rather than a selective, deficit of memory. In an attempt to adjudicate between these competing positions, Smyth and Naveh-Benjamin (2016) discussed 2 sets of experimental data that they claim speak against the global deficit model. Here I review some general principles of how the global-deficit view is applied to experimental paradigms and demonstrate that even a simplified form of DRYAD can comfortably accommodate the critical findings cited by Smyth and Naveh-Benjamin. I also evaluate aspects of their results that may be problematic for DRYAD and describe ways in which DRYAD's account of associative recognition can be falsified. I end with a discussion of the complementary strengths and weaknesses of the 2 approaches and consider ways in which the associative deficit hypothesis and DRYAD might work more profitably together than apart.

Keywords: aging, associative recognition, DRYAD, memory, associative memory

The experimental study of the effects of aging on memory goes back nearly 100 years (Ruch, 1933; Willoughby, 1929), but the stakes for understanding age-related memory decline have never been higher. The world's population is aging rapidly, and older adults shoulder greater responsibilities for self-care than ever before. Advances in combatting societal and personal difficulties that will arise in this "graying" world will clearly depend on having an accurate characterization of the relationship between aging and cognitive skills.

Within cognitive psychology, theoretical progress has stalled in part because of a virtually unbreachable division between two general camps. In one camp, populated principally by experimental psychologists, it is proposed that memory decline results from specific, selective deficits. The other camp includes (but is not limited to) researchers who adopt a psychometric approach to the study of aging and mostly attribute age-related decline to a global, widespread deficit in memory fidelity. Two theoretical contenders within these respective camps are the *associative deficit hypothesis* (ADH), which proposes a *selective* deficit in retaining associations between memoranda, and the *density of representations yields age-related deficits* (DRYAD) model, which proposes that a *global* age-related deficit affects memory most dramatically for information that is sparsely encoded. In this short comment, I outline some of the motivating principles underlying DRYAD, review how a new associative-recognition version of DRYAD confronts the data reviewed by Smyth and Naveh-Benjamin (2016), and suggest further avenues for exploration in contrasting the two general approaches.

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DRYAD and the Global-Deficit View

DRYAD was an attempt in part to reconcile the discrepant results and theories across experimental and psychometric camps of researchers. It is, most centrally, a proof-by-demonstration that empirical interactions—such as the greater deficit in memory for source evident in older adults (Spencer & Raz, 1995)—can be obtained in a memory system in which the deficit is global, not specific. A point of crucial importance to DRYAD is that interactions are not revealing of process dissociations (see also Loftus, 1978; Wagenmakers, Krypotos, Criss, & Iverson, 2012). Even disordinal interactions, such as ones in which a manipulation increases the false-alarm rate in older adults but decreases it in younger adults (e.g., Benjamin, 2001; Benjamin & Craik, 2001; Jacoby, 1999) are easily handled by a system in which only a general deficit is imposed (Benjamin, 2010).

DRYAD is, like any other theoretical endeavor, an attempt at simplification. It simplifies the problem of cognitive aging into a single parameter—memory fidelity. I and my collaborators are under no illusion that such a claim can be true, strictly speaking—such a claim would belie the hugely multidimensional and variable nature of human personality and cognition. Certainly, at the very least, there must be cohort differences between the sprightly, active older adults who volunteer for experiments in university laboratories and the indifferent undergraduates who mostly participate out of obligation. But the goal of DRYAD is not to articulate a full-throated summary of the effects of aging on cognition. It is to test the extent to which such simplifying assumptions can provide an account for data that have been taken to *necessitate* complex, multiprocess, selective-deficit theories. The fact that DRYAD can simulate somewhere between most and all major findings in the voluminous literature on aging and source memory does not by itself compel one to accept the theory that those effects reflect a global deficit, but it does mean that those effects do not rule out such a global-deficit theory. The additional facts that DRYAD aligns with the outcomes of nearly all psychometric studies of aging and cognition, and that it has given rise to predictions that have been confirmed, are reasons to view the global-deficit perspective favorably.

One of the desiderata that Benjamin (2010) employed was to find a representational scheme that would avoid having to postulate what "items," "contexts," "associations," and "sources" are. The perspective that Benjamin took was similar to the one taken by Gallistel and Gibbon (2000) in their seminal analysis of conditioning data. Gallistel and Gibbon pointed out that the concept of the "trial" is one that makes experimental sense but is unlikely to exist in the head of the animal being studied; they developed a unified framework of classical and operant conditioning by construing the passage of time and the rate of events as the basic units of analysis, rather than the progression of trials. Similarly, Benjamin pointed out that if one avoids theorizing in terms of items and contexts and rather considers how variable conditions of learning direct attention and promote memory, then one can explain why the aspects of stimuli that we call "contexts" are often less interesting, less memorable, and more prone to experiment-wide interference than are the things we call "items."

From that alternative perspective, it is straightforward to understand why contexts that are designed to be of interest to older adults, such as personality characteristics rather than gender (Rahhal, May, & Hasher, 2002), and emotional rather than perceptual or conceptual information (May, Rahhal, Berry, & Leighton, 2005), eliminate the age-related deficit in memory for source. That perspective also leads to a set of predictions about how direct manipulations of attention should be able to reverse the nature of the age-related deficit. Those predictions were confirmed by Benjamin, Diaz, Matzen, and Johnson (2012), who showed that older adults exhibit a deficit in whatever aspect of a multidimensional stimulus is deemphasized during encoding and also that younger adults whose encoding is curtailed exhibit a greater deficit for deemphasized than emphasized aspects of stimuli. These results are incompatible with the ADH in the absence of additional post hoc theorizing about boundary conditions on the associative deficit or alternative mechanisms that usurp the normal associative processes.

One of the reasons that DRYAD is implemented in a computational model is to avoid the undue flexibility that often accompanies verbal theorizing. DRYAD avoids all questions about what constitutes a context versus an item—in fact, it eschews such terms entirely. It might seem straightforward to assume that a pair of words constitutes two items and one association, but this interpretation relies on untested assumptions about how we parse our conceptual world. If a pair of words is encoded via an association, then how do we encode a pair of letters? Does a representation of a word really contain pairwise associations of the component letters? What about a list of words that follows a particular set of ordering rules—sometimes called a sentence (cf. Jacobs, Dell, Benjamin, & Bannard, in press)?

None of this is to deny that the brain might operate in such a way as to divide the world up into items and contexts, as well as associations between those things. It is merely to say that we cannot assert any one representational scheme by fiat. The representations employed by DRYAD are agnostic to nomenclature—a memory is nothing more and nothing less than a set of encoded elements. Whether those elements are thought to reflect items or associations does not matter to DRYAD (though it might to the subject and experimenter); yet, it yields behavior that appears to the experimentalist to reflect such divisions. The ADH, in contrast, is a position that is simple to articulate but affords simultaneously too little and too much flexibility. It has vast degrees of freedom associated with how one defines the boundaries of an item, yet it allows no room for individuals to engage in idiosyncratic encoding of events or for stimuli to enjoy the compositional character that is central to forms of knowledge more complex than individual words. The recent revitalization of interest in the concept of "unitization" is a good illustration of how the one-size-fits-all model of encoding strategy fails to capture important strategic differences that individuals bring with them to memory tasks (e.g., Bastin et al., 2013). Most tellingly, in failing to recognize that the memory for any study event involves both contextual and focal elements, it elides the question of how relevant prior experiences are remembered and irrelevant ones ignored.

Associative Recognition and Aging

The accompanying report by Smyth and Naveh-Benjamin (2016) questions the generality of the logic of DRYAD to memory for associative information. They consider source memory and context memory paradigms to be special cases of associative memory—memory for items that are bound to one another. In the typical associative memory paradigm, words are presented together during study and the requirement for the subject at test is to discriminate between intact pairs and rearranged pairs. In the experiments covered in greater detail by Smyth and Naveh-Benjamin, words are presented in differing fonts, and the association refers to the word–font pairing. The bulk of their argument is reflected in the two reported experiments (the first of which is taken from Naveh-Benjamin, 2000, Experiment 3). Their findings can be summarized as follows:

1. When words are studied in variable fonts, the magnitude of the age-related deficit for the word–font pairing is greater than the magnitude of the age-related deficit for either words or fonts alone.

2. Dividing the attention of younger adults does not decrease memory for word–font pairings more than it decreases memory for words and fonts alone.

3. Instructions to attend to words or fonts selectively enhance memory for the attended aspect of the stimulus and decrease memory for the unattended aspect.

4. Encoding instructions elicit a decrease in memory for the contraindicated information to a greater degree in younger than older adults.

Not all of these results fall within the purview of either DRYAD or the ADH. Specifically, claims about the effect of encoding instructions require an additional set of theoretical assumptions about how those instructions affect encoding strategies. Such assumptions are additionally complicated by the possibility that the age groups respond differently to them. Younger adults in psychological experiments are typically college students, who may be quite comfortable with obeying arbitrary instructions issued by authority figures, because that is what much of undergraduate education consists of. Older adults may be less likely to take such instructions at face value and may also suffer from a greater degree of stereotype threat in memory experiments (e.g., Hess, Auman, Colcombe, & Rahhal, 2003). The fact that older adults engage different brain regions during encoding (Anderson, Iidaka, & Craik, 1998) and reveal qualitatively different costs on a secondary reaction time task (Anderson, 1999) indicates that such concerns are warranted.

All of this is to say that the effect of encoding instructions to attend to one aspect of a stimulus or another may have complicated effects that differ across groups. Finding 4 might be taken to reveal a less-focused spotlight of attention in older adults, a claim that is widely made in the visual attention literature (Hartley, Kieley, & Slabach, 1990; Madden, 1984; Plude & Hoyer, 1986) and that has been generalized to episodic memory search (Benjamin, 2011). The result is revealing about memory only if one assumes equivalent obedience, attentional dispersion, and encoding strategies across age groups. Because that's a theory about attention and motivation, rather than about memory, we have no additional truck with it here. Similarly, Finding 3 is a claim about how an attentional bottleneck engenders tradeoffs in encoding among the dimensions of a stimulus. Benjamin (2010) used similar logic to demonstrate the effect of attention on memory for sources. It is quite easy to account for such results using DRYAD, but the success of such a venture bears not one bit on the validity of the differential claims about memory representations made by Benjamin (2010) and Smyth and Naveh-Benjamin (2016). From this point forward, I focus on the more-relevant results embodied in Findings 1 and 2. These findings also provide a considerably greater challenge to global-deficit models.

It is worth noting the many commendable qualities of the data in question, because those qualities directly influence the validity of these findings. Most important, the involved experiments avoid two confounds typical to experiments using source memory tasks. First, the number of items and fonts is equated. This aspect of the design equates certain aspects of interference across the two stimulus dimensions, a move that is rarely taken in the source memory literature. Second, the two test types (item vs. associative recognition) rely on the same yes/no procedure. These procedures reduce the difficulty involved in directly comparing the two tests. In addition, their use of a detection-theoretic dependent measure means that the treatment of the measurement scales as having interval-level qualities can be defended. Yet, contrary to the claims of Smyth and Naveh-Benjamin (2016), little about these results is incompatible with even a very simplified version of DRYAD, as reported in the simulations summarized below.

Simulation of Associative Recognition Using DRYAD

There are several ways in which DRYAD can perform associative recognition. Reviewing all of the options would require a more in-depth review of DRYAD than is possible here; the interested reader is directed to Benjamin (2010) for details. One option would be to force the model to rely solely on the retrieval mechanism to "recollect" the particular association between two words, the familiarity of each of which would be nondiagnostic (cf. Kelley & Wixted, 2001). However, this strategy would of necessity force a reliance on different mechanisms for item recognition and associative recognition. Success in simulating a data pattern using such an approach would be far less convincing than would an approach in which associative and item recognition utilize the same memory representations and the same memory-access processes.

The simpler strategy pursued here is to allow DRYAD to encode into a single memory representation information about a "word" and a "font," to degrees that we see as consistent with the instructions and affordances of the task, and then evaluate using only the matching (familiarity) mechanism to assess recognition of old (compared to new) words, of old (compared to new) fonts, and of intact (compared to rearranged) word–font pairings. Figure 1 shows the learning and testing for this simulation schematically. On each trial, a word–font pairing is encoded into the DRYAD's memory with a degree of fidelity governed by the learning parameter. The noise generated by that process applies to the entire memory trace, regardless of whether a particular dimension represents information about the word or about the font. Later, item recognition is tested by presenting an intact item with no font information, and font recognition by presenting the font without the word. Associative recognition is tested by comparing the recognition signal to intact versus rearranged pairs, just as in the typical experimental design.

DRYAD relies on the global-matching mechanism proposed by Hintzman (1986); critically, the nonlinearity in this function allows the model to successfully differentiate between intact and rearranged word–font pairings. Even if a word and font are both stored in memory, the match will be greater if those items are stored within the same memory trace. Figure 2 summarizes the results of a large-scale simulation of word recognition, font recognition, and associative recognition using only the matching mechanism. This particular simulation allocates six dimensions toward the allocation of word stimuli and four toward the allocation of font stimuli because fonts are generally less distinctive from one another than are words (and the human data appear to bear that claim out). Nothing about the important results changes as a function of the choice of dimensionality, however.

The top panel of Figure 2 shows how word recognition, font recognition, and associative recognition increase as the learning parameter is increased. The important result to notice is that recognition of words and fonts increases linearly, whereas recognition of word–font pairings increases nonlinearly, with its concavity up. In other words, there is an increase in the *rate* at which associative recognition increases with each unit of learning as

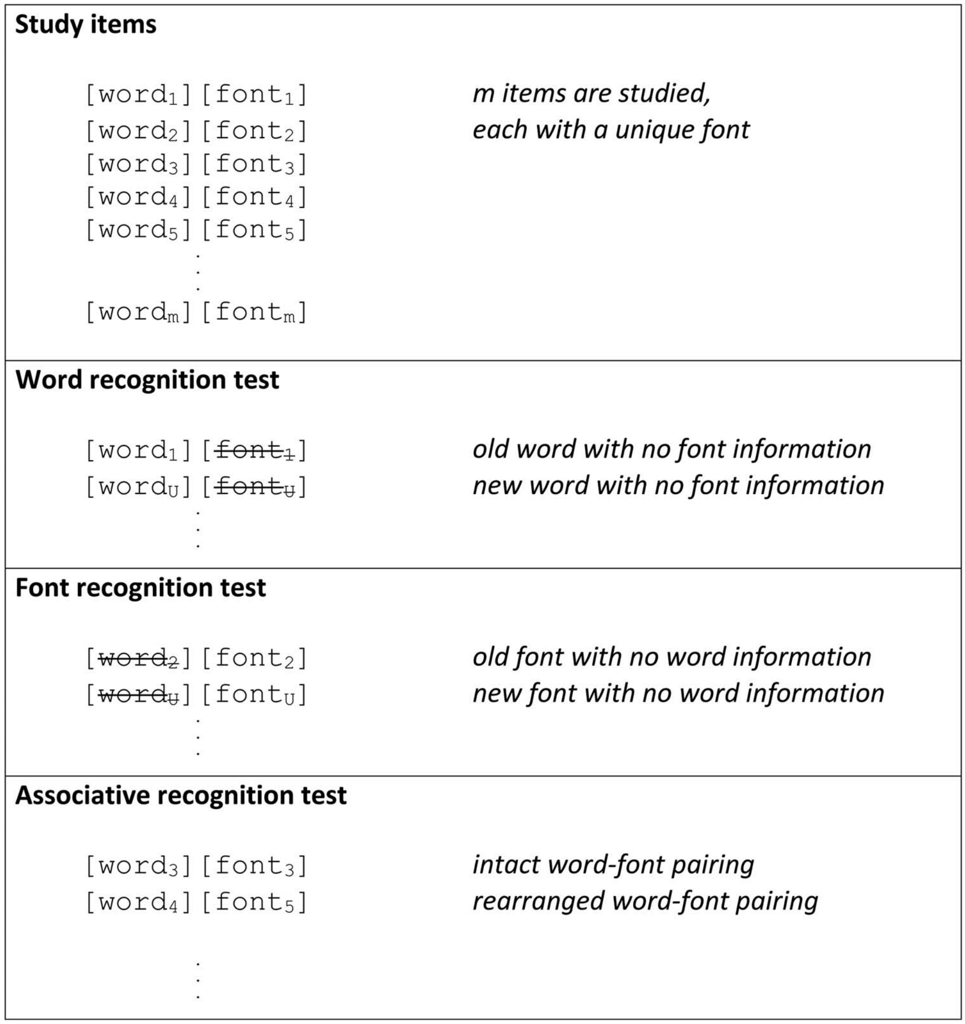

Figure 1. Simulation of word recognition, font recognition, and word–font associative recognition in the *density of representations yields age-related deficits* (DRYAD) model. Crossed-out items indicate that the details were not included in the memory trace.

overall learning goes up. It is this fact that enables DRYAD to account for Findings 1 and 2: It can either predict a disproportionate decrease in associative recognition or not, depending on the overall degree of learning.

The bottom two panels illustrate this claim with example data drawn from the top panel. In the left graph, learning is varied in the high end of the parameter space ($F > .9$) and it is easy to see that the net effect is greater for associative recognition than for recognition of individual words or fonts. This result is analogous to Finding 1: If the lower parameter value represents the memory fidelity of older adults and the higher value of younger adults, then this is a simulation of the most central finding in the literature on aging and associative memory: Older adults suffer more on the associative recognition task than on the word or font recognition tasks. Varying the learning parameter in a lower range of the space ($.64 \leq F \leq .76$) yields Finding 2: The division of attention lowers performance but does not do so disproportionately for associative recognition over the other tasks.

I recognize that a certain amount of hand-wringing is in order, given this state of affairs. Essentially, these simulations tell us that DRYAD can just as happily predict a disproportionate decrease of associative recognition as not, depending on where conditions sit with respect to the learning parameter—a set of results that might be taken to reveal legerdemain on the part of DRYAD. At the very least, this is a circumstance that might lead us to wonder whether DRYAD is telling us anything at all. Perhaps it is simply too flexible to be of much use as a theoretical tool?

Flexibility of the Competing Theories and Ways in Which DRYAD Can Be Falsified

The flexibility of DRYAD is a serious concern; two points especially merit consideration. First, though excess flexibility is rarely a virtue in any theoretical position, the flexibility of computationally formulated theories is readily apparent, measurable, and often remediable with the addition of additional assumptions.

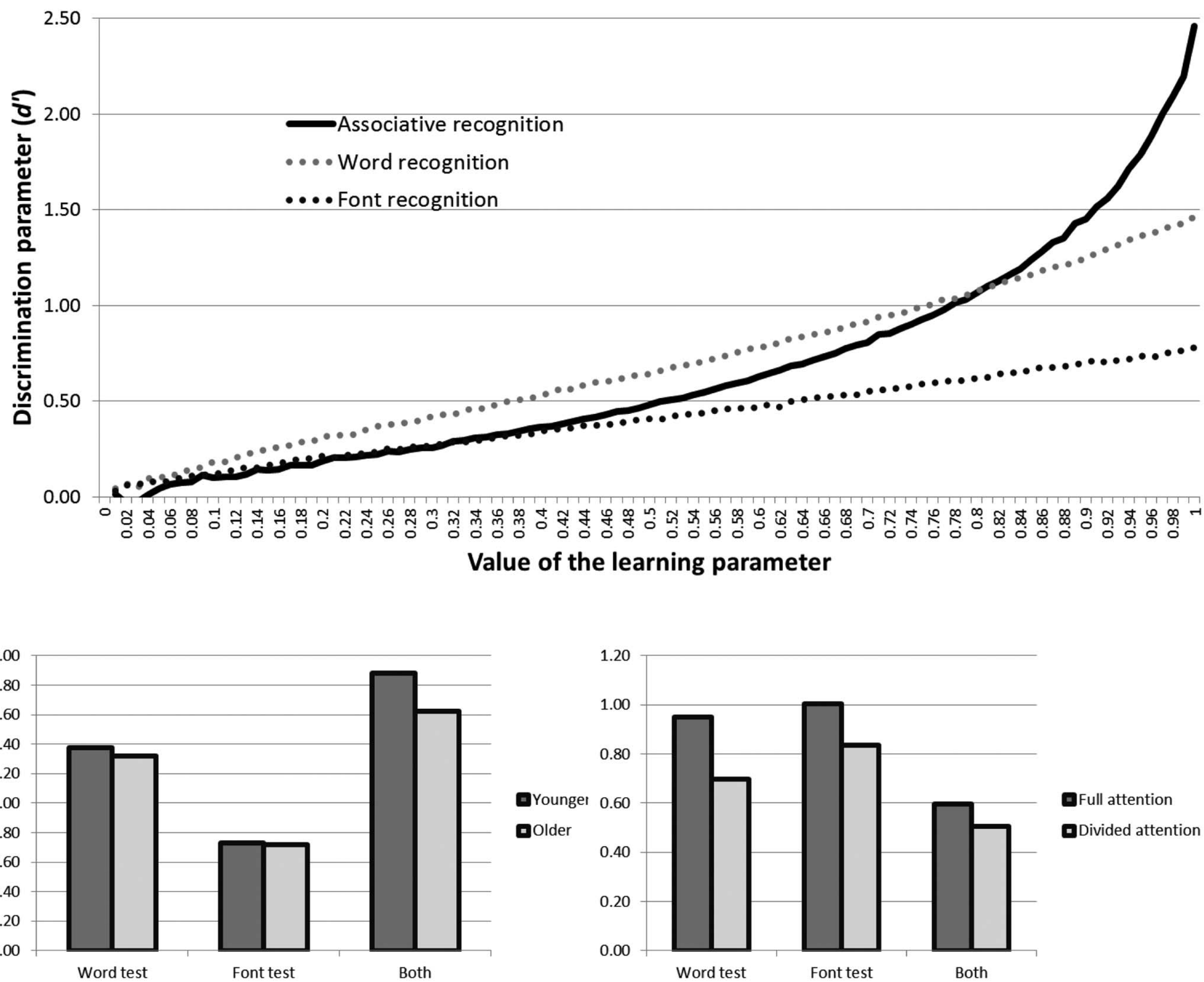

Figure 2. Results from the *density of representations yields age-related deficits* (DRYAD) model simulation outlined in Figure 1. The top panel shows the effect of varying the learning parameter (F) from .01 to 1.0 on word recognition, font recognition, and associative recognition. The simulation included six dimensions allocated toward words and four toward fonts. The recognition criterion was 0.12. The bottom two panels show examples of data drawn from the top figure. In the left panel, a single manipulation of learning (F = .93, F = .96) affects associative recognition more than does either word or font recognition—similar to in Smyth and Naveh-Benjamin's (2016) first experiment. In the right panel, a single manipulation of learning (F = .64, F = .76) affects associative recognition less than does either word or font recognition—similar to in Smyth and Naveh-Benjamin's (2016) second experiment.

In contrast, the flexibility of a verbally formulated theory like the ADH is apparent only when the formulator confronts problematic data. This is where the arbitrariness of dividing the world into items, associations, and contexts is clear: It is quite easy to simply rejigger one's partitioning of the stimulus space after one sees the outcome of an experiment. Thus, the reduction or elimination of the age-related associative memory deficit under conditions of elaborative encoding (Naveh-Benjamin, Brav, & Levy, 2007), under intentional learning (Naveh-Benjamin, 2000), and when the stimuli enjoy a preexisting semantic relationship (Naveh-Benjamin, Hussain, Guez, & Bar-On, 2003) are not seen as evidence that is contrary to the ADH but rather as circumstances under which relevant preconditions are not met. And even if one constructs a reasonable story about why those experimental cases truly merit alternative explanations, then one is still faced with other cases that require alternative, alternative explanations. Why, for example, does the associative deficit disappear when the contexts are changed from names to personality characteristics (Rahhal et al., 2002; cf. Siedlecki, Salthouse, & Berish, 2005) and *reverse* when memory for the associations is tested implicitly (by their influence on future intentional learning; Campbell, Hasher, & Thomas, 2010)?

A second important point is that, DRYAD's flexibility notwithstanding, Figure 2 reveals two clear ways in which the version implemented here could be rejected as a model of the age-related deficit in associative recognition. First, because the associative recognition function is concave up and the item recognition functions are roughly linear, *the disproportionality of the age-related deficit should be greater at higher degrees of learning.* Thus, though DRYAD can produce an age-related associative recognition deficit, it is not clear that it can produce it in the same range of performance reported by Smyth and Naveh-Benjamin (2016). Collapsing over the encoding instruction in their first experiment yields a disproportionate age-related deficit on an associative recognition test, the mean performance of which lies in between the mean performance on the item recognition tasks. It does not appear to me that the version of DRYAD reported here can simulate this particular ordering of tests along with the age-related associative deficit, at least within the parameter ranges that I explored. Whether this pattern could be accounted for with a fuller version of DRYAD, and whether this aspect of the empirical age-related deficit is determined to be critical and replicable, await further development.

Second, according to DRYAD, *there are no conditions in which older adults could simultaneously exhibit superior item recognition and impaired associative recognition relative to younger adults.* More generally, older adults can always demonstrate intact or impaired performance relative to younger adults but never superior performance on one measure but an impaired performance on the other. This prediction is valid as long as one can be assured that the other parameters (the dimensionality of word and font representation, in this case) remain constant over the conditions. The curves shown in Figure 2 are part of a family of potential curves that vary with the dimensionality of the word representation and the dimensionality of the font representation. Those two degrees of freedom cannot produce a family in which any of those curves drops as F is increased.[1]

In the first experiment reviewed by Smyth and Naveh-Benjamin (2016), there are some encoding conditions (attend to fonts, as well as attend to word–font pairings) in which word recognition is *numerically* higher for older adults (and associative recognition is lower). If the higher performance of older adults in that condition can be convincingly shown to be more than roughly equivalent performance in the presence of statistical noise, particularly under conditions in which the test trials are intermixed (and thus that F can be assumed to be roughly equivalent within a group across tests), then those would also be quite difficult data for this version of DRYAD to handle.

Contrasting DRYAD and the ADH

Perhaps it is now apparent that DRYAD and the ADH live in fairly separated spheres of existence. The ADH is a reasonable response to the data pattern that arises quite regularly, indicating that age affects memory for things that appear to be conjunctions of stimuli more than things that appear to be single stimuli. However, it requires a theory, tacit or otherwise, of what constitutes an item and an association, and it is inconsistent with results in which the age-related deficit is reduced by manipulations of interest (May et al., 2005; Rahhal et al., 2002) or attention (Benjamin et al., 2012).

DRYAD has an orthogonal set of strengths and weaknesses. It exhibits flexibility in predicting age-related associative deficits, but it's not clear that that flexibility can extend to the wide range of circumstances in which the associative deficit is found. It avoids theorizing about what aspects of stimuli are items versus associations, but it lacks any explanation for the origin of the age-related deficit and is only suggestive of variables that influence the dimensionality of its representations.

An important lesson to be learned from the data reviewed by Smyth and Naveh-Benjamin (2016) and the simulations reviewed here is that evaluating the prospect of theories with intuition is a venture that is at best limiting and often misleading. DRYAD may or may not in the final analysis be able to account for the complexity of the associative-recognition data, but it is clear that the aspects that seem to be the most obvious points of failure for the model are not the ones in which it will actually come up short. The construction of a computational model is exceptionally useful in this regard—it can ground such debates and reduce the degrees of freedom available to the theorizer in response to new data.

There may be more ways in which the core theoretical suggestions contrasted here can coexist than ways in which they can be profitably differentiated at an empirical level. Benjamin (2010) even noted that one possible origin of the global deficit might be an associative deficit. It is a widely recognized but rarely discussed fact that all recognition is a form of associative recognition. Subjects are rarely if ever asked whether they have *ever* seen a particular word or font before; rather, they are asked whether they have seen them before in the particular context of the study episode during the experiment. To the degree that all recognition is a form of context-bound associative recognition, a failure to appropriately include contextual elements in a memory trace would yield a global deficit. In doing so, the ADH is rendered a global, rather than a selective, deficit, a move that eliminates the views' incompatibility.

Similarly, other suggestions from the pool of selective-deficit theories are compatible with DRYAD when the "selective part" is reconsidered to be applicable to a broader range of events or at a different level of analysis. *Inhibition* is, for example, an alternative basis for the global deficit in DRYAD—if the rememberer lacks the resources to focus on individual elements of a memorandum at the exclusion of others well enough to encode those elements faithfully, then the result will be a lower fidelity memory trace (cf. Hasher, Stoltzfus, Zacks, & Rypma, 1991).

There can be no doubt that the associative deficit is an empirical reality: When conditions are constructed that follow one's intuitions about how people will divvy up stimuli into items and associations, older adults truly are more commonly deficient in remembering the associative part. No global-deficit view denies this fact; it is merely suggested that the empirical interaction need not require a psychological dissociation. When task conditions, as well as limitations on measurement, are taken seriously into account, global-deficit theories provide a comfortable and powerful means of understanding the origin of

[1] Though do note that the familiarity and retrieval mechanism working in conjunction can produce nonmonotonic learning functions, as shown in Figure 6 of Benjamin (2010) and Figures 5 and 6 of Benjamin, Diaz, Matzen, and Johnson (2012).

such empirical interactions and a means of reconciling the appearance of selective deficits with generalized loss of ability.

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