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Explaining Short-Term Memory Phenomena with an Integrated Episodic/Semantic Framework of Long-Term Memory

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Abstract

Current thinking about human memory is dominated by distinctions between episodic and semantic memory and between short-term memory (STM) and long-term memory (LTM). However, many memory phenomena seem to cut across these distinctions. This article attempts to set the groundwork for the issues that need to be resolved in generating an integrated model of long-term memory that incorporates semantic, episodic, and short-term memory. We contrast Nairne's (2002, *Annual Review of Psychology*) consensus account of short-term memory with a relatively generic theory of an integrated episodic-semantic memory. The latter consists primarily of a list of principles which we and others argue are necessary to include in any theory of long-term memory. We then add some more specific assumptions to outline a modern theory of forgetting. We then turn to the issue of much of the phenomena thought to necessitate a dedicated short-term memory can be explained by an integrated theory of episodic and semantic memory. Our conclusion is that an integrated theory of long-term memory must be augmented to explain a small number of outstanding memory phenomena. Finally, we ask whether the augmentation needs to involve a dedicated mnemonic system, or sensory or language-based systems, which also have mnemonic capabilities.

Explaining Short-Term Memory Phenomena with an Integrated Episodic/Semantic Framework of Long-Term Memory

Current thinking about human memory is dominated by distinctions between episodic and semantic memory (Tulving, 1972) and between short-term memory (STM) and long-term memory (LTM) (Atkinson & Shiffrin, 1968; Baddeley & Hitch, 1974). However, many of the memory phenomena which require explanations seem to cut across these distinctions. For example, Baddeley (2000) started with a very well-developed model of STM but added a not-so-well specified store by way of the episodic buffer. The function of the episodic buffer was to allow for the contributions of semantic and episodic memory via binding of the different sources of information. In a similar vein Farrell (2012) proposed a model of serial order effects in episodic memory that was derived in most part from ideas prevalent in the STM literature. We, on the other hand, are doing much the same as Baddeley and Farrell but are starting from the perspective of well-established principles of episodic memory and are going to examine how both pre-existing knowledge is developed and used, and to examine to what extent a separate STM system is needed to provide a relatively integrated account of memory.

Nairne (2002) in his review article distilled the essential ideas circulating at the time in what he called the “standard” model of STM. According to Nairne STM is an adaptive, dedicated system for keeping recent information in some kind of accessible form. Activation (of long-term representations) is seen as the basis of short-term storage. That is, cognitive processing leads to the activation of a number of highly accessible memory traces. However, Nairne notes that such activation is fragile, with decay of activation being the primary source of forgetting. Activation can be restored or refreshed via rehearsal. Thus, STM represents the dynamic interplay between decay of activation and its replenishment through rehearsal. This simple and elegant model explains many of the characteristics that are thought to discriminate STM from LTM such as limitations in capacity, immunity to the effects of prior learning

(proactive interference or PI), rapid forgetting through decay, and activation based retrieval. The only STM characteristic missing from this list is the dominant role that phonological codes appear to play on immediate tests of verbal tasks memory tasks.

However, as Nairne notes, the standard model appears to violate well established tenets of memory theory. For instance, the notion of forgetting due to decay has been largely rejected in the face of empirical evidence supporting interference as the mechanism that results in forgetting. Computations in STM are heavily based on activation but although there are some important exceptions in general memory theory, items do not possess mnemonic properties outside specific retrieval contexts. That is, it is accepted that memory retrieval is cue driven, not activation-based. While these differences can be viewed as providing additional need for the separation of short-term and long-term constructs, the fact is that much of the empirical evidence supporting the standard model has been eroded over the last two decades (Nairne, 2002 details much of the earlier evidence), such that current models of serial recall definitely see immediate recall as being cue-based.

Nairne also offers the beginning of a “standard” model of episodic memory in his characterization of episodic memory being cue-based with interference as the primary source of forgetting. These ideas were reinforced by Surprenant and Neath’s (2009) specification of four principles of episodic memory. These are: a) the dependency of memory on cues, b) the cue overload principle, c) the reconstruction principle and d) the importance of discriminability.

Surprenant and Neath’s (2009) reconstruction principle is very well supported. It seems impossible to observe new learning which is not affected by prior learning at both short- and long-retention intervals. That is, knowledge about word-order in sentences, phoneme order in words, facial features and their relationship to other facial features, and the elements in scenes and their relationship to other elements, all affect memory. Memories can

even be created out of separately activated components. For example, we will be discussing data sets where a non-studied word is recalled based on the information activated by an extra-list or part-word cue and the information activated by a contextual cue. However, if one rejects the assumption that reconstruction is simply guessing from semantic memory if retrieval from episodic memory fails, then there are relatively few ideas in the memory literature about how semantic information can constrain episodic retrieval and how it can be prevented from overwhelming episodic information. There are also few ideas in the memory literature about how to characterize the knowledge that gets transmitted from semantic memory to episodic memory and how memory and learning are structured so that it is possible for semantic information to constrain episodic retrieval.

We provide an account, drawn from a variety of literatures, about how this interaction between episodic and semantic memory is possible and how it is controlled. We start with an examination of the computational constraints on the use of semantic information in episodic retrieval that have been examined in the memory literature. These constraints address the linked problems of how the semantic information can be used and how it can be prevented from overwhelming the episodic retrieval process. We then argue that representations and the links between them constitute the knowledge that influence episodic memory. In order to help make representations relevant to a memory context, we start with Humphreys and Hannah's (under review) characterization of memories (e.g., for objects or locations) as representations, which can enter into associations with other representations. We also draw upon Humphreys, Li, Burt, and Loft's (2020) position, drawn from the language production and reading literatures, that the things we call *words* are collections of closely linked phonological, orthographic, and articulatory representations, as well as a more abstract representation. These component representations are linked by learnable connections and can enter into episodic associations with each other and with other representations. Next,

we look at systems consolidation in an attempt to understand how learning and memory are structured so that semantic memory representations can affect episodic memory retrieval. Systems consolidation refers to the findings showing that for a period of time after new learning a functioning hippocampus is necessary for the retrieval of the new learning. However, if the new learning is strengthened its retrieval no longer depends on a functioning hippocampus. If new memories are stored in the hippocampus and are only slowly transferred to the cortex there is an obvious problem in allowing the knowledge stored in the cortex to affect new learning, other than by being used as a guess if the retrieval of the new learning fails. However, neurological theories of systems consolidation (Morris, 2006; Teyler & DiScenna, 1986) have proposed that hippocampus does not store new memories, and instead stores pointers to memories/representations stored in the cortex. We review this work, its implications for forgetting, and most importantly, show how it answers the problem of making the information stored in the cortex (semantic memory) available to constrain retrieval from episodic memory.

After reviewing how memories can function as representations and the structural and processing assumptions needed to allow semantic memories to contribute to episodic retrieval, we comment on the implications for current distinctions between episodic and semantic memory, and between the memories of organisms which associate an incoming stimulus with a memory and the memories of adult humans.

Next, we turn Nairne's (2002) and Surprenant and Neath's (2009) ideas about episodic memory being cue dependent and forgetting being due to interference (cue overload) into a relatively generic connectionist or global matching model. We do this by making some additional structural and processing assumptions. The most important of these is that some memory tasks such as cued recall with an extra-list cue and cued recall with a part-word cue requires a retrieval function that approximates the computation of an intersection. That is, we

assume that the experimenter provided cue activates the set of its associates and a list context cue activates the items from the list. Then the two sets are combined in a manner approximating an intersection. This is the retrieval function that we discuss in the section on computational constraints on how semantic information constrains episodic retrieval. We also assume distributed representations in order to, amongst other things, expand on Surprenant and Neath's (2009) concept of discriminability. Surprenant and Neath were concerned with situations where the memory items were distributed along a single dimension such as length. The concept of noise (Humphreys & Chalmers, 2016) subsumes the single dimension situation and any other situation which makes memory retrieval or discrimination more difficult. The assumption of distributed representations may not be essential. That is, it is possible that any theory that accounted for the data regularities which we point to would suffice. In keeping with the idea that memory is cue dependent we also assume that contextual cues play an essential role in controlling memory access and that context can change quite rapidly in an orderly way, or it can be disrupted (Howard & Kahana, 2002; Humphreys, & Chalmers, 2016; Smith & Vela, 2001).

The structural and processing assumptions which we have just described are used to address a number of issues which together address the question as to whether separate STM and LTM systems need to be postulated. The first is to address what a modern theory of forgetting would look like which incorporates both cue overload and a role for both orderly and disruptive changes to context. Next we examine results from the short-term cued recall paradigm. This paradigm is clearly in the short-term domain as a large majority of the retention intervals used fall in the range of two to five seconds. The findings involving the role of phonological information are also cited in the STM literature as being supportive of a dedicated STM system. However, the results also, show that there is a substantial amount of continuity across the short- and long-term domains in the use of prior knowledge, cues,

context, and noise. Following on from the argument about an essential continuity between the short- and long term domains we first address the closely linked issues of immunity to proactive interference (PI) and capacity limitations which have been used to argue for the need for separate STM and LTM systems. Our analyses of the tasks involved and the evidence for rapidly changing contextual cues suggests that the data in this area does not compel the postulation of separate STM and LTM systems.

We then examine the role of decay as an alternative to interference as a cause of forgetting along with the linked idea that a persistence of activation of the retrieval target plays a major role in determining the likelihood of retrieval. Note that activation is an extremely useful metaphor and we have almost no choice but to talk about items being activated by cues or to assume that in learning pairs of items the first item activated remains active long enough for it to become associated with the second item. The question we address is whether activation plays a role when an item in a short list is not activated by a cue and whether activation would have to last for more than perhaps two or three seconds or persist past the presentation of another item or cue. However, we will show that there is informative data in the existing STM literature, as well as in new analyses of recency effects in free association which finds little or no evidence for decay or activation persisting for more than two to three seconds.

An analysis of the existing literature on the role of articulatory/phonological information in retention over short-term and long-term domains completes our analyses of the phenomena which are assumed to compel the postulation of separate STM and LTM systems. The data supports that differences in the use of articulatory/phonological representations differentiates retention in the short- and long-term domains. However, for most of the results this differentiation seems to follow from the characteristics of articulatory/phonological information not from STM per se. This analysis is greatly aided by the assumption that there

are a variety of representations linked to what we call words and that these representations can enter into associations with each other.

Our analysis of the role played by articulatory/phonological information in retention over short intervals along with some observations by Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, and Usher (2005) on differential PI effects in immediate free recall and continuous distractor paradigm, suggest that there was a need to postulate separate STM and LTM systems. The next question we address is whether the kind of dedicated system identified by Nairne (2002) is required or whether all that is needed is the postulation of a handful of separate modules whose principle function need not be mnemonic. In addressing this issue it became apparent that it was not easy to define what a dedicated STM system is because STM theories can consist of a set of modules which can have functions other than strictly mnemonic functions (Baddeley & Hitch, 1974). An evolutionary argument would be required to identify the principle function and it is unlikely that general agreement could be obtained. In lieu of an evolutionary argument, the theorist's intentions and the target audience can be taken into consideration. If the module is presented as part of an overarching theory of STM, the theory for the particular module borrows heavily from the theories for the other modules, and the target audience are STM researchers not perceptual or linguistic researchers, it seems appropriate to consider the module as a dedicated STM module.

In our final section we consider whether the account that we have outlined and our analyses are going in the right direction.

Initial Steps Towards an Integrated Semantic/Episodic Framework of LTM: Computational Constraints, Representations and Structure

Ebbinghaus (1885) invented the nonsense syllable in an effort to study new learning independently of prior learning. However, one of the most important post-Ebbinghaus findings is that new learning is probably never independent of prior learning. Participants add meaning to the so-called nonsense syllable (Kausler, 1974; Pavio, 1971), serial strings are easier to recall the more closely they approximate the participants language (Miller & Selfridge, 1950), and pre-existing associations contribute to paired-associate learning (Humphreys Murray, & Koh, 2014, Palermo & Jenkins, 1964; Wicklund, Palermo & Jenkins, 1964), and to associative recognition (Doshier & Rosedale, 1991; Naveh-Benjamin, Guez, & Marom, 2003). Same race faces are also better recognized than different race faces (Tanaka, Kiefer, & Bukach, 2004).

It is also apparent that both episodic and semantic memory factors influence performance in the short-term domain. Thus, language factors like word frequency (Watkins, 1977), concreteness (Roche, Tolan & Tehan, 2011), and grammatical function (Tehan & Humphreys, 1988) influence immediate serial recall, as does membership of semantic categories (Poirier & Saint-Aubin, 1995), and the degree of associative relatedness among list items (Tehan, 2010; C. S. Tse, 2009). Such influences reflect the structure and organisation of pre-learned semantic and lexical knowledge to STM that come under the umbrella term of semantic memory. In addition, in immediate serial recall repeating a string after a delay, which should have removed any STM trace, increases the probability that a participant will recall the repeated string (Hebb, 1961). Likewise, there are intrusions from the same list position in the immediately prior list (Estes, 1991; Henson, 1998). These kind of intrusions are very unlikely to occur unless the cue used to recall the STM for the item in position k in the last list also cues the LTM for the item in position k in the prior list.

In order to address the need to have old learning contribute to new learning and to avoid overwhelming interference from that background knowledge we outline what we believe are

the essential characteristics of an integrated theory of episodic and semantic memory. We still allow for some differences between episodic and semantic memory but we are convinced that they must work together in order to explain the influence of old learning on new learning.

Bindings and intersections

Identifying the essential components of an integrated episodic and semantic memory means that there are a number of problems to be solved, the first of which involves the computational problems involved in using semantic memories to augment episodic memories. In particular, how to use both a semantic cue and a contextual cue to retrieve a semantically related item from a list even when the semantic cue was not paired with the semantically related item in the list (cued recall with an extra-list associate as a cue). The problem is, as Tulving (1972; also see Tulving & Thomson, 1973) argued, that episodic memory requires an episodically unique memory so that the episodic cue and the semantic cue are not pointing to the same memory. We also consider the flip side to this question which is how to avoid recently acquired and presumably weak episodic memories from being overwhelmed by far stronger semantic memories.

Ideas about how to prevent pre-existing knowledge from overwhelming new learning comes from Humphreys, Bain and Pike (1989; also see Doshier & Rosedale, 1997). Humphreys, et al. (1989) looked at the problem of protecting new learning in the crossed associates paradigm (pre-existing associations such as *spider web* and *grass green* are repaired *spider green* and *grass web*) from the much stronger semantic memories between the semantic cue and its associate. They concluded that a three-way association or binding (a holistic cue) was required between the target, associative cue and a context cue. Humphreys, et al. (1993) extended this analysis to the AB ABr paradigm with lists consisting of two pairs

(list 1 AB CD list 2 AD CB). Humphreys, et al. asked the question as to whether the second list could be learned via pairwise associations (cue to target and context to target) without producing massive interference. With pairwise associations after several training trials on list 1 and just a few training trials on list 2, the A to B and C to D associations will be strong relative to the A to D and C to B associations. In addition, the association between the list-2 context and the targets will be equal for D and B. Thus, there will be substantial interference relative to that found in the AB AD paradigm where the cue is the same in the two lists but new targets are used in list 2. This occurs because the association between the list-2 context and the list-2 targets can compensate for the stronger association between A and the list-1 target (B) than between A and the list-2 target (D). However, the interference observed in AB ABr learning is approximately the same as the interference observed in the AB AD paradigm (Barnes & Underwood, 1959; Yim, Dennis, & Sloutsky, 2013; McGovern, 1964; Porter & Duncan, 1953). Thus, the AB ABr paradigm also requires the use of a three-way binding or holistic cue involving the two pair members and the list context. Such a binding supplies information about the joint occurrence of the cue and the target in the list.¹

The crossed associates and the AB ABr tasks illustrate the need to prevent pre-existing memories from producing excessive amounts of interference. Cued recall with an extra-list associate illustrates the need to use semantic knowledge in an episodic recall task. In cued recall with an extralist associate participants study a list of words and are then given

¹ It is important to note that we are using binding in the computer science sense where it does not necessarily refer to an entity. Something must be stored but the process of using that stored information can also contribute to the ability of the system to represent the three-way information. For example, in Minerva II Hintzman (1984) represents words as vectors and the memory for a pair is stored as the concatenation of the two vectors. For an associative recognition test Hintzman concatenates the two vectors corresponding to the test pair and matches (takes the dot product) the concatenated vector against every pair stored in the memory. Each match with a stored memory is then raised to the third power before the individual match strengths are summed producing the overall match strength. Without the step where the individual matches are raised to the third power this process would provide information about the two test words having occurred in the list but without raising the individual match strengths to a power greater than 1.0 there would be no information about whether they had occurred together. The Minerva II example demonstrates that bindings, as we are using the term, are not entities.

cues that are semantically or conceptually related to one of the words in the study list. The participants are asked to use the cue to recall the related word from the list. The problem for memory theory is to explain how the cue enhances recall of the target, because the cue did not occur with the target in the study list.

One way to explain the enhancement of recall without assuming that the semantic cue directly activates an episodic memory is to assume that at study the target activates the cue strengthening the cue-target association (Humphreys & Galbraith, 1975; Storms, 1958). An alternative on this basic idea was proposed by Polyn, Norman, and Kahana (2009). They assumed that the associates activated by the target when it is studied became part of the list context which is then used in conjunction with the experimenter supplied cue in the retrieval attempt. There are several problems with this approach. One is that it does not appear to be able to explain why the forward association from the cue to the target is considerably more important than the backward association from the target to cue, and why cues can be successful when there is a forward association even if the backward association is close to zero (Nelson & Goodmon, 2002). Similarly, Tehan, Humphreys, Tolan, and Pitcher (2004) used a category label as a cue when the list did not contain a category instance. Under these conditions, the presence of a rhyme of a category instance (e.g., the cue is *tool* and *trench*, a rhyme of *wrench*, is in the list) resulted in relatively frequent production of false memories (e.g. *wrench*). Without the presence of the target in the study list there is no backward association to activate the associates. We can also be confident that the rhyme in the study list was not activating the target because there was no effect of the presence of the rhyme when participants were given free association instructions (use the cue to produce the first category instance that comes to mind).

Another alternative to enhance recall without assuming that an extralist cue directly activates an episodic memory was proposed by Morton and Polyn (2016). They suggested

that the experimenter supplied cue contained features which overlapped the features in the semantically related list word so that the experimenter supplied cue could directly activate the memory for the semantically related list word. The problem with this approach is that it has problems explaining why words which elicit the list word in free association norms are more effective cues than words which are semantically related but which do not elicit the word in free association. The superiority of free association in predicting the effectiveness of cues not only violates linguistic intuitions (Moss, Ostrin, Tyler, & Marslen-Wilson, 1995) it is contradicted by similarity ratings (Napps, 1989). For a more extensive discussion of the similarity of words see (Humphreys & Hannah, under revision).

As an alternative to both a backward association and featural overlap, Humphreys, Wiles, and Bain (1993) proposed that in cued recall with an extralist cue the cue would activate its associates and suppress all other words and a contextual cue would activate the words in the list and inhibit all other words. Then the two sets would be combined in a manner approximating an intersection, such that only the associate of the cue that was on the list was not suppressed. Thus, previously learned information contributed to episodic recall but much of that information was suppressed by the context cue.

Humphreys et al. discussed several ways in which an intersection could be accomplished. The one favoured was a connectionist model using sparse representations (Wiles, Humphreys, Bain, & Dennis, 1991). Humphreys, et al. (1993) also explained how the SAM model (Raaijmakers & Shiffrin, 1981) could also be used to calculate this intersection. Subsequently both Sirotn, Kimball, and Kahana (2005) and Kimball, Smith, & Kahana (2007) proposed the same solution involving SAM. However, as Humphreys et al. (1993) had noted, SAM only works as a model of paired-associate learning (one member of the study pair is used as a cue for the other member) if an episodically unique memory is stored when the list is studied. This was a feature of the original version of SAM as it stored

a separate image each time a word was studied. This assumption of a separate image was changed by Shiffrin, Ratcliff, and Clark (1990) who assumed that, at least within a list, the image would be the same every time a word was studied. In order for SAM to work as a model for paired-associate learning, the image which is activated by the extralist cue has to be the same as the image which is activated by the list specific contextual cue. This means that there is only a single image so that the image stored in list 1 of the AB ABr paradigm has to be the same as the image stored in list 2. As Humphreys et al. (1993) noted this meant that while SAM could be used to model cued recall with an extralist cue if the same image was activated by both the extra-list cue and the contextual cue, that version of the SAM model predicted massive interference in the AB ABr paradigm.²

This inability to simultaneously bring the knowledge stored in semantic memory to bear on episodic learning and to prevent massive interference in other situations can be easily fixed if a model can utilise both three-way bindings and calculate intersections of activated sets. However, there is probably an even more important lesson to be learned. By assuming that the extralist cue and the list specific contextual cue both activate the same “thing”, Sirotnin et al. (2005) and Kimball et al. (2007) fundamentally altered the psychology and the underpinning neurology of Raaijmakers and Shiffrin’s (1981) model. The second of our problems involves understanding just what kind of assumptions one has to make about psychology and neurology in order to make sense of the assumption that a common “thing” is activated. Next, we will look at representations as the common “thing” which is activated,

² The version of SAM adopted by Sirotnin et al. (2005) and Kimball et al., (2007) does not necessarily predict massive interference in the crossed associates paradigm. The reason for this is that Sirotnin et al. and Kimball et al. borrowed the assumption from Raaijmakers and Shiffrin (1981) that cues could be used with different weights. The adoption of a low weight for the semantic cue would reduce interference in the crossed-associate paradigm. However, this solution would not work if pairs created out of crossed associates and associatively related pairs were included in the same study list.

and then look at some ideas about systems consolidation to see why it makes sense that a common “thing” could be activated.

Representations

In order for both a semantic and an episodic cue to work together in retrieval the two cues must point to the same “thing”. Representations are the “things” cues point to. With a few important exceptions, theories of STM and LTM traditionally did not address the issue of representations in any depth, until the advent of psycholinguistic theories of STM (Jefferies, Frankish, & Ralph, 2006; R.C. Martin, Lesch & Bartha, 1999; N. Martin & Gupta, 2004). These researchers view STM effects as emerging from interactions between mechanisms that support order information, and the phonological and semantic codes or representations underpinning word recognition and language production (Burt & Humphreys, 1993; Levelt, Roelofs, & Meyer, 1999; Oppeinheim, Dell, & Schwartz, 2010; Perfetti, 1992; Perfetti & Hart, 2002; Plaut, McClelland, Seidenberg & Patterson, 1996).. There has been less impact of psycholinguistic theories on conceptualizations of LTM though there are now two recent articles that address relevant issues about how representations are created and how they interact (Humphreys & Hannah, under review; Humphreys, et al., 2020). These articles make three points about representations which we believe need to be included in any theory of LTM.

The first point is that episodic memories can function as representations, in that they can stand in for the original stimulus which gave rise to the memory. This provides the starting point for arguing that the “things” we call words consist of a relatively “abstract” representation plus closely linked sensory representations such as articulatory and phonological representations. Like other representations the representations linked to a “word” can enter into episodic associations with the other representations of that word. In addition, like other representations the pre-existing associations between the representations

can be strengthened whenever one representation activates another representation (e.g., the phonological representation activates the more abstract representation). In support of memories serving as representations Humphreys and Hannah (under revision) referred to a paper on two-year-old children (Akhtar & Tomasello, 1996) and another with rats (Bae, Holmes & Westbrook (2015). In the Akhtar and Tomasello paper, the children first played with a novel but unnamed toy. Sometime later they were provided the name of the toy when it was not physically present. The evidence that they had associated a name with a previous memory came when, provided with the name, they identified the toy presented amidst an array of other toys and when shown the toy they named it. In the Bae et al. paper, the rats learned an association between a shock and a memory for an environment even though they were in a novel, though similar environment, when the shock occurred. This was not a case of transfer of training because they did not learn an association between the shock and the novel environment in which the shock occurred due to having only been placed in the novel environment shortly before administration of the shock. The critical point of both examples is that episodic memories can stand in for or represent the initial stimulus which gave rise to the memory.

The second point is that with the episodic memories discussed in the previous paragraph, the similarity between the representations (e.g., between the visual representation of a dog and the visual representation of a cat or the phonological representation of *wrench* and the phonological representation of *wench*) is closely linked to the similarity between the stimuli that gave rise to those representations. Humphreys and Hannah also proposed that *child* representations could be created from two *parent* representations (e.g. the visual and phonological representations of dog) such that the similarity between the child representations was different than the similarity amongst the parent representations. That is, that a more abstract (less dependent on physical similarity) representation could be created.

In order to illustrate how this more abstract representation could occur, Humphreys and Hannah referred to a two-year-old child who was pointing to objects that were then named by an adult. In this scenario they proposed that phonological information derived from the adult would be processed in processor A and visual information derived from the object would be processed in processor B. It was also assumed that both A and B processors randomly projected to a third processor C. They then outlined how the similarity relationships within the A and B processors could be dramatically different than the similarity relationships within the C processor if the only neurons or features remaining active in the C processor were those that had received input from both the A and B processors³. This assumes that the similarity structure in processor A is uncorrelated with the similarity structure in B. That is, the names of two similar visual objects are not similar and two phonologically similar names are not visually similar. Although this explanation is speculative it does suggest that a relatively simple process could underlie a relatively abstract representation of concrete words and has the implication that the abstract representations of most words are not as similar to each other as are the parent representations. It is also consistent with a large body of research showing that list length effects with words are quite small (Buratto & Lamberts, 2008; Dennis & Humphreys, 2001; Dennis, Lee, & Kinnell, 2008; Kinnell & Dennis, 2011, 2012)⁴ and that with taxonomic categories category-length effects are quite small (Cho & Neely, 2013; Maguire, Humphreys, Dennis, & Lee, 2010).⁵

³ Humphreys and Hannah (under revision) were extending the idea that the intersection of the two sets activated by different cues could be used to retrieve a memory to the formation of a new memory.

⁴ In these experiments morphemic relatives, function words and technical terms are typically not used and may well have higher degrees of similarity than the words used. Nevertheless, the words used are frequently randomly drawn from large corpuses, with some restrictions such as word length, and are broadly representative of the words in daily use.

⁵ These results were surprising because in the global matching models, word similarity had been used to explain list and category length effects (Clark & Gronlund, 1996). Within the context of the global matching models, small list and category length effects require low levels of similarity amongst the words.

The third point about representations is that what we think of as a “word” actually consists of multiple representations with learnable connections amongst representations. That is, a word consists of a phonological representation that is linked to a more abstract representation which is referred to as a lemma in the language production literature and as a lexical entry in the reading literature. In turn the lexical representation is linked to an articulatory (output representation). If Humphreys and Hannah are correct in their conclusions that words are not very similar to each other, this abstract representation of a word does not have all of the properties that have been attributed to the lemma or the lexical entry. However, this information could be obtained via associations between the lexical representation and other representations. Such associations would include those with embodied representations about what animate objects look like, how they move, or the noise they make and what inanimate objects look or feel like and how they can be used. In addition, the strength of the connections between these representations (e.g., the phonological and the lexical) are not at asymptote and can change whenever one representation activates the other. Humphreys, et al. (1989) noted that retrieval with part word cues was partially modality specific, regardless of whether cued recall instructions or instructions to produce the first word that came to mind that completed the cue were used. That is, the probability of recalling or producing the word in the study list that matched the cue was greater if both the study list and the cue were presented in the same modality. They suggested that the assumption of a connection between phonology and a more abstract representation of the word that could be strengthened when it was used and weakened when a similar phonological representation activated its more abstract representation could explain the modality specificity. Burt and Humphreys (1993) provided support for this conjecture by showing that the naming response was slowed if a word which was spelled similarly but pronounced differently had occurred 10 items earlier in the naming task. Such learnable connections between representations are now

an accepted part of the language production literature (K.R. Humphreys, Menzies, & Lake, 2010; Oppenheim et al., 2010) and should be considered in the memory literature.

Systems Consolidation

The third problem we address is how the representations pointed to by an episodic cue such as a list context can be the same as the representation pointed to by a semantic cue even though the memory for the occurrence of the referent in the study list or episode can still be considered as being episodically unique. It is widely believed that the hippocampus functions to bind the different components of an episode together. It rapidly forms these bindings but overtime at least some of them become independent of the hippocampus. That is, for a time after initial learning damage to the hippocampus disrupts memory performance, but if enough time has elapsed since encoding then hippocampal damage no longer disrupts memory performance. The process of memories which initially required the hippocampus to become established, to subsequently becoming independent of the hippocampus, is referred to as *systems consolidation*. There is no fixed time limit as to how long an undamaged hippocampus is needed for consolidation to occur (Morris, 2006; D. Tse et al., 2007, 2011). For example, D. Tse et al. (2007) had rats learn six odor-place pairings. After these pairings had been well learned, two new odors paired with two new places located nearby the old places were learned. Only a single reinforced trial was administered for the new odor-place pairings. A single non-reinforced test trial administered after 24 hours showed that the new associations had been learned. Hippocampal lesions were made 24 hours later, 48 hours after initial learning. After the animals had recovered from the operation, test trials revealed that they still remembered the newly acquired odor-place associations. This is much shorter than the usual time needed for systems consolidation with this odor-place pairing paradigm (Morris, 2006).

There have been several variations on the basic idea that the hippocampus implements the early stages of the binding process (McClelland, McNaughton, & O'Reilly, 1995; Squire, Cohen, & Nadel, 1984). The variant which we are most interested in was proposed by Teyler and DiScenna (1986) and expanded on by Morris (2006). The essence of Teyler and DiScenna's idea was that the hippocampus was structured and anatomically situated to capture information about neocortical activity generated by the individual features of a behavioral episode. Moreover, because the hippocampus projects back to those neocortical regions, the information stored in the hippocampus could serve as an index or pointer to the pattern of neocortical activity produced by the episode. Consequently, a partial cue that activated the hippocampal index could activate the neocortical patterns and thus retrieve the memory of the episode. Morris (2006) argued that there was no need to store a large amount of sensory and perceptual detail about an episode in the hippocampus and that indeed it would take up too much storage space. In addition, a reliance on only the information that could be stored in the hippocampus would not make effective use of all the knowledge stored in the cortex about grammar (how words are put together to form phrases and sentences), how the features of a human face are arranged, how words are created out of a string of phonemes, and other areas where a knowledge of what usually occurs aids in the retrieval/reconstruction process.

As an illustration about how Morris' (2006) idea might work, consider a pair (AB) of items which might consist of a pair of words, a name-face pairing, or an odor-place pairing. When this pair is presented it seems possible that no direct connection in the cortex would be established due to the overall low level of connectivity in the cortex.⁶ Instead, the activation

⁶ As summarized in the Morris paper the average connection probability in the cortex is only $1:10^7$ while most CA3 pyramidal cells are connected via two or three synaptic steps

resulting from the presentation of A would meet up with the activation resulting from the presentation of B in the hippocampus. At the same time associations from the hippocampus back to the cortex would be formed. It is possible that these backward associations would follow a path that was parallel to the input path. The advantage of this assumption is that the pointer in the hippocampus only has to point to where a specific input came from, and not to every place in the cortex where a paired stimulus might come from. Thus when A is presented as a cue for B it will activate A's representation in the cortex which in turn flows into the hippocampus where it meets up with the pathway to the hippocampus which was started by the presentation of B. Then this activation will flow along the route on which the activation resulting from the presentation of B came into the hippocampus. The result will be the near simultaneous activation of the representations of A and B in the cortex which will promote the learning of a direct connection between those cortical representations. Over time with additional pairings of A and B or additional retrievals of one representation given the other, or a rehearsal like process occurring during sleep (see Cirelli & Tononi, 2015, for an overview), the direct connection between A and B will be strengthened to the extent that the cortical memory becomes independent of the hippocampus (see Fig. 1).

It is now possible to see why in our section of representations we only discussed embodied representations which might be described as episodic memories. That is, a memory which had been formed in a small number of encounters with a novel toy (Akhtar & Tomasello, 1996), or a memory which had been formed after a short period of time in a novel environment (Bae, et al., 2015). We suggest that the relationship between hippocampal and cortical learning means that all of the representations reside in the cortex. Some representations require an intact hippocampus to be retrieved and others do not. However, once representations are activated, they all function as representations in the same way.

As indicated by the D. Tse et al. (2007) results, direct connections within the cortex can be established in a single learning trial if connections linking nearby areas also exist. It is possible that it will be easier to directly link some types of pairs than others. For example, face-face pairs may be easier to link than face-name pairs because the representations of the former will be found closer together in the cortex and be more likely to have a pre-existing or be close to a pre-existing connection. As we will discuss later, other types of learning may be supported by specialized structures/processes in the cortex such as the position-item bindings that seem to be required to explain serial recall and to explain learning how to pronounce novel words (Majerus, 2013). In addition, if an existing association exists in the cortex it will be strengthened by either recall or the paired presentation of the component parts.

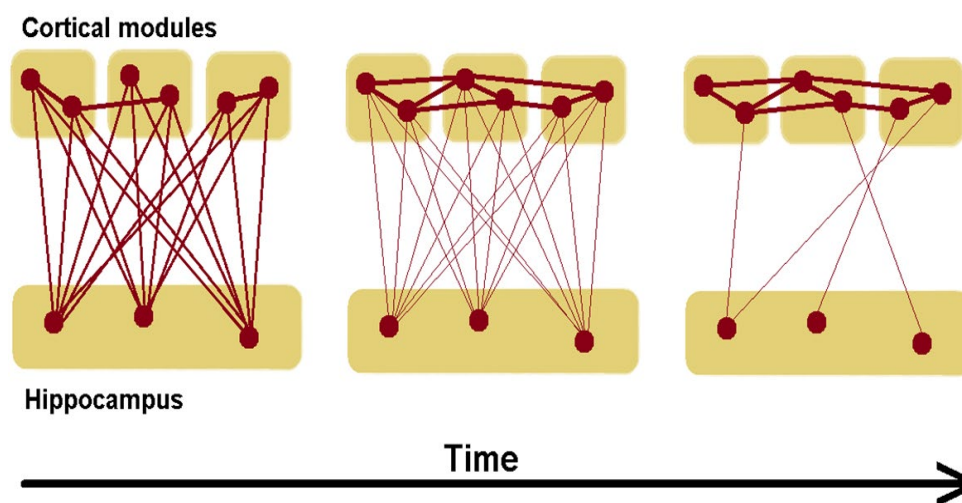


Figure 1. Initially the neurons in the cortex are unconnected or only partially connected so the integrity of the memory requires input from the hippocampus. Over time the cortical neurons become more strongly connected and the connections from the hippocampus weaken and disappear.

If the conjecture about the low level of connectivity in the cortex being responsible for failures of cortical learning is correct it could explain the persistent failures to teach people with a damaged hippocampus an association between two unrelated words (Clare & Jones, 2008). As we have noted, words in general do not seem to be very similar to each

other. If low levels of similarity imply low levels of neuronal overlap it would explain these failures to learn new associations between unrelated words.

The primary advantage of the relationship between the hippocampus and the cortex, which we have outlined, is that new learning can take full advantage of the structural information about the characteristics of human faces, the constraints on how words are ordered in phrases and sentences, the likelihood of the transitions between one phoneme and another in a word, and the presence and arrangement of features in an environmental scene (e.g., of a beach). Another advantage of this relationship between the cortex and the hippocampus is that it provides a common workplace where information activated by a semantic cue and information activated by an episodic cue can be combined.

Thus, we are proposing that there are at least two types of “long-term” memories. Some memories require a functioning hippocampus to be retrieved. We will refer to these memories as *hippocampal dependent memories*. Others can be retrieved without the aid of a functioning hippocampus. We will refer to these as *hippocampal independent memories*. Of course, some memories will be retrieved using both hippocampal and cortical connections. It would also be conceptually possible to distinguish between memories which are established without preliminary help from the hippocampus and memories which needed that preliminary help to become established.

The differentiation of hippocampal dependent memories and hippocampal independent memories means that the information stored in the cortex can contribute to the learning of serial order, cued recall and pair recognition. It also means that when the memory for a studied word is cued with a semantic cue and an episodic contextual cue, the two cues are cueing the same “thing”. The availability of holistic cues linking a pair of words with the context in which they were studied also enables the system to dampen down the contribution of the semantic system when it would hinder, not help performance.

The status of the episodic- semantic distinction and the difference between non-human memories and the memories of adult humans

The theory where the hippocampus serves as pointers to representations stored in the cortex has similarities to the memory systems proposed by Humphreys, et al. (1989) and McClelland et al. (1995). However, it is a substantial departure from the memory system diagrams about semantic and episodic memory found in many introductory textbooks. What compels this divergence is the need to make the information stored in semantic memory available to new learning. The Bae et al. (2015) and Akhtar and Tomasello (1996) examples where low-verbal and non-verbal organisms associate an incoming stimulus with an activated memory so that the association transfers to the stimulus which originally gave rise to the memory also challenges the idea that conscious awareness and mental time travel (the ability to be aware of the past and to anticipate future states) are the defining properties which separate adult episodic memories from the memories of non-verbal organisms and young children (Michaelian, 2016; Suddendorf & Corballis, 2007; Tulving, 1995, 2002).

Because we can identify non-verbal organisms that have a memory/representation that can substitute for the original experience, we can tell that in this important way their memories/representations are like the representations of adult humans. These organisms need not be consciously aware of an activated memory/representation, but their memories/representations would be a precursor to conscious awareness and mental time travel. We can also identify organisms that do not have that kind of memory/representation. This difference between non-verbal organisms can be seen in how they respond to a sudden change in the magnitude of reward. Crespi (1942) showed that rats trained to approach food in a runway quickly altered their running speed when the magnitude of the reward changed. It appeared that they had a memory for the magnitude of the reward they had previously

received which could be compared to the magnitude of the reward that they had just received. However, Gonzalez, Potts, Pitcoff and Bitterman (1972) showed that fish responded only gradually to a change in the magnitude of a reward suggesting that they did not have a memory for reward magnitude.

Organisms which can associate an active memory with an incoming stimulus can, with the aid of a recurrent environment anticipate a future state such as scrub jays avoiding a favorite food because they were anticipating that the food had become decayed (Humphreys & Chalmers, 2016, chapter 7). However, organisms which do not have a memory for reward magnitude or for an environment in which an aversive event had occurred might be conscious of the stimuli impinging on them but without an internal state that can stand in for a stimulus, they would not be capable of anticipating a future state or of being aware of the past.

This distinction between the kind of memory a fish has and the kind of memory mammals and presumably birds have is not captured in current distinctions between procedural and declarative memory and within declarative memory between episodic and semantic memory. James (1890) described memory proper as “the knowledge of a former state of mind after it has already dropped from consciousness (p. 648).” James goes on to say “The first element which such a knowledge involves would seem to be a revival in the mind of an image or copy of the original event (p. 649).” Although James was relying on introspection in his assertion that such a memory involved a revival in the mind, introspection is not necessary. All that is required is to show that an activated memory can be associated with an incoming stimulus, and that the new association transfers to the original stimulus that gave rise to the memory. It would be appropriate to call the type of memory which mammals and birds but not fish have a Jamesian memory. This would leave it to future research to decide whether the clearly superior ability of adult humans to plan for the future involves a fundamentally different ability or whether it is produced by some or all of the following three

possibilities. These are the development of language, a large increase in capacity including the ability to store higher order associations, and the extended childhood where children are taught how to control their memory (see Humphreys & Chalmers, 2016).

How Much Can an Integrated Semantic/Episodic Framework Explain about STM: Cues, Context, Reconstruction, and Noise

To this point we have developed a background that outlines the constraints on a theory of LTM, focusing on the need to distinguish between different types of binding and using an intersection process involving item/category and context cues as a retrieval mechanism. We have also spoken about representations, their function and how they are formed and developed into our existing knowledge base that forms the background to episodic recall. We have not addressed the issue of forgetting in any detail, nor have we developed the concept of context. In the earlier section we indicated that the relationship between cues and targets were crucial and that, equally crucially, this relationship was moderated by the context in which cues and targets were studied and tested. We will now develop each of these ideas and examine how such ideas transfer to the STM domain. In doing so we move away from a broad generic model of memory to one where we draw upon assumptions about parallel processing and distributed/superimposed representations.⁷ However, we intend our account to be a relatively generic version of connectionist and global matching models.

We start by outlining a modern theory of associative interference supplemented by a theory of context. Then we review results from the short-term cued recall paradigm showing that there is substantial continuity in the use of prior knowledge, cues, context, and noise

⁷ By distributed/superimposed representations we mean that multiple items are represented over the same set of units (e.g., neurons or nodes in a connectionist model) so that it is possible that any one unit is involved in the representation of many different items. For a more detailed discussion see Humphreys & Hannah (under revision) and van Gelder (1992).

across the short- and long-term domains. We then examine the STM literature in light of the theory of forgetting and the demonstration of continuity across the short- and long-term domains to see whether five phenomena, require separate theories of STM and LTM. The first section addresses the complicated narratives about how immunity to PI can sometimes be observed with immediate tests on short lists and how limits on memory capacity can occur. The second section addresses the equally complicated narrative of the evidence for decay versus associative interference and the role of item activation in memory access. The third section explores the similarity and differences between the role of articulatory/phonological information in the short- and long-term domains.

A Modern Theory of Associative Interference Supplemented by a Theory of Context

The basic idea behind associative interference is that recall becomes more difficult when more than one target is subsumed under a cue (Watkins & Watkins, 1975). Although interference was intended to apply to a wide range of memory paradigms it was primarily investigated using paired-associate learning paradigms. In the interference paradigms, participants learn two lists of pairs where the relationship between the cues and/or the targets in the two lists is manipulated. The interfering effects of learning the second list on the memory for the associations learned in the first list is referred to as retroactive interference (RI). What list-1 learning does to a memory for the associates learned in list 2 is referred to as PI.

There is overwhelming support for the forgetting, or at least an inability to recall the appropriate response, due to an AB AD relationship. There is also no reason to believe that either systems consolidation or cellular consolidation⁸ would render a memory immune to the

⁸ Cellular consolidation refers to physiological changes at the cellular level that are supposed to protect the memory against disruption by electro convulsive shock or protein formation inhibitors.

effects of learning additional cue target associations after having learned the original association.

The AB AD paradigm produces interference when the A term is used to cue memory but not when the B term is used (McGovern, 1964). This is one line of evidence which suggests that interference is primarily due to response competition (with A as a cue both B and D compete) and is not primarily due to trace destruction (the B to A association is intact). The other line of evidence against explaining interference in terms of trace destruction comes from the effects of interference on associative recognition. Dyne, Humphreys, Bain, and Pike (1990) had participants study AB, AC, and DB pairs before testing on the intact pair AB. Participants also studied EF, GH, EI, and JH pairs before testing on the rearranged pair EH. In the baseline conditions participants only studied AB, EF, and GH before being tested on AB and EH. The effect of this manipulation was to increase both the hit and false alarm rates by nearly the same amount. These findings are compatible with global matching models which match a test pair against every pair in memory, accumulating evidence over the different matches. If the intact pair AB is tested it will match the memory for AB from the study list, the memories for AC and DB pairs from the study list, plus other memories from the list or from prior events. The overall “matching strength” is the sum of all of the individual matches. Because the overall matching strength is increasing, not decreasing, the memory is not primarily destructive. It is true that if the false alarm rate is increasing faster than the hit rate then discriminability is declining (Cohn & Moscovitch, 2007; Verde, 2004). However, this kind of gentle degradation is very different than ideas about obliterating the memory trace. These results also show that AB AD interference manifests itself in different ways in recall and recognition.

Associative interference in the paired-associates paradigm depends to some extent on the spacing between lists, which probably indicates a role for a temporal context. For

example, the second list in the AB AD paradigm does not show evidence for PI as it is being learned. It is learned at about the same rate (trials to criterion or total number of errors) as the second list in the AB CD paradigm. PI is only apparent when a retention interval is introduced after the second list. Similar findings occur in the Brown-Peterson paradigm. There is little or no interference observed when the retention interval following the last list is short compared to the interval between the last list and the earlier lists (Loess & Waugh, 1967). The best explanation for this and related findings such as the long-term-recency effect (Bjork & Whitten, 1974) is that a changing temporal context can protect recent memories from earlier memories. In their review of context, including temporal context, Humphreys and Chalmers (2016) went beyond the usual focus on the effects of reinstating the physical context. Instead they also discussed the effects of reinstating the conceptual context, the effects of disrupting context, switching between recall tasks, and attempts to see if recalling or recognizing from a list reinstated part of the study context. In addition, they examined whether results obtained by using a specific cue (e.g., one member of a study pair), in addition to a generic cue such as a category label which subsumed all of the targets in a list, could help to understand what performance would look like if subjects were using a contextual cue in addition to a specific cue. For more information on temporal contexts see Howard and Kahana (1999, 2002), Sederberg, Howard, & Kahana (2008) and Lohnas, Polyn, Kahana (2011). When this very broad range of evidence is taken into consideration the case for the importance of a context that can change quite rapidly but can be reinstated via instructions, and the retrieval of memories learned in that context, becomes overwhelming.

If a changing temporal context is dependent on an intact hippocampus, then the ability of context at short retention intervals to protect against interference implies that hippocampal dependent memories and hippocampal independent memories will react differently to PI and RI. That is, without hippocampal learning, new learning in the cortex will not be isolated

from older memories. As a result, older memories (e.g., a memory that event A is sponsored by brand B) will compete with the new memories that are being learned (e.g., learning that event A is now sponsored by brand D). This will slow the new learning down but there will be no increase in interference with an increase in the retention interval. An increase in interference with an increase in the retention interval is characteristic of learning which is supported by a changing temporal context. In contrast RI may play a larger role when only cortical learning is involved than when learning also involves context and the hippocampus. That is, there may be a limited ability to reinstate the list-1 context (Humphreys & Bain, 1985; McKenzie & Humphreys, 1991) with hippocampal learning but there would be no such ability with cortical learning which would not involve context.

Disruptions also seem to produce a change in context harming retrieval (Humphreys & Chalmers, 2016). For example, in a directed learning paradigm, participants learn two lists. After learning the first list they are either asked to remember it or to forget it. Then after learning the second list both groups are given an unexpected recall test for both lists. The usual result is that the group which was instructed to forget performs more poorly on the first list than the group instructed to remember. Sahakyan and Kelley (2002) showed that the poor performance also occurred if participants were instructed to think about something else such as a tour through their house following the learning of the first list. Thus, a disruption to context seems to produce the same effect as instructions to forget suggesting that both effects are due to context disruption. More support comes from Humphreys, Murray and Maguire (2009) who gave participants several training trials on a list of cue-target word pairs. Then participants had a single study trial on a series of shorter (4-pair) lists. After every 4-pair list had been studied two cues were presented. The first cue was either for a target in the most recent 4-pair list or for a target in the longer well-learned list. After the participant had responded to the first cue the second cue was presented. This cue was always for a target in

the 4-pair list.⁹ In one experiment the words in the 4-pair lists were the same words that were used in the longer lists but the pairings were never the same. In the traditional paired associate terminology this is an AB ABr paradigm. Participants were very good at separating their memories for the 4-pair list from their memories for the well learned list even when the same words used in the long lists were also used in the short lists. In addition, when the first recall came from the long list there was more interference with the second recall than when the first recall came from the short list. It seems likely that participants would have to maintain a pointer of some kind (context) to the long list in order to be able to shift their attention from the 4-pair list in order to recover a memory from the earlier list. This is especially evident when the words in the long list were also used in the 4-pair lists. It thus appears that shifting context is more disruptive than just recalling.

Another example of an apparent loss of memory due to a disruption of context and not to associative interference comes from forgetting intentions when people walk through doorways. This forgetting has also been attributed to the disruption of context (Radvansky, Krawietz, & Tamplin, 2011). Thus, there is substantial evidence that contextual disruption impairs recall. Given this it seems possible that even a brief period of mind wandering during a retention interval could disrupt context and cause forgetting that might otherwise be attributed to decay (Berman, et al., 2009).

Whether or not a theory of associative interference, even when supplemented with a theory of context, can provide a comprehensive account of normal forgetting¹⁰ remains an open question. For example, Wixted (2004) argued that the AB AD paradigm was seldom encountered in real world settings and that Underwood (1957) had overestimated the effects

⁹ When the first cue was from the short list, the target of that cue was never the target of the second cue presented.

¹⁰ By normal forgetting we mean to exclude interventions explicitly designed to interfere with neurological parameters such as electro convulsive shock or damage to the hippocampus.

of PI.¹¹ However, some important instances of interference due to AB AD learning have been investigated. McAlister, Kelly, Humphreys, and Cornwell (2012) conducted field studies where the sponsor of an event had recently changed. In an internet survey one group of fans were asked to recall the sponsors of an event one week after the event and a second group was asked to recall after six months. In all four studies the recall of the replacement sponsor declined from the one-week retention interval to the six-month retention interval and the incorrect recall of the old sponsor increased. What seems to be happening is that, ignoring context, the memory for the old sponsor is stronger than the memory for the new sponsor (more time or opportunities to learn) but this strength difference is masked by the ability to use context to focus on the most recent memory. However, as the retention interval increases this ability to focus on the most recent memory dissipates and the probability of recalling the older but stronger memory increases. One can think of other examples such as holders of political office and sporting championships where AB AD interference is also likely to be found.

Nevertheless, there are many situations where interference appears to be present but there is no observable AB AD relationship. Included are list length effects (Kinnell & Dennis, 2012), category length and strength effects (Baumann, Vromen, Boddy, Crawshaw, & Humphreys, 2018; Konkle, Brady, Alvarez, & Oliva, 2010a, 2010b), interference when A is studied by itself after having studied AB (Overton & Adolphson, 1979), and in the memory for complex scenes. In order to explain the interference which occurs in these tasks and to address whether associative interference can provide a comprehensive account of forgetting we need to consider both the use of context as a retrieval cue and distributed representations.

¹¹ Weeks, et al., (2007) also argued that Underwood (1957) had overestimated the effects of PI but for a different reason. Weeks et al. argued that the noise arising from the other pairs in the list would also be forgotten, slowing down the apparent rate of forgetting.

With distributed representations it is possible to extend the basic ideas about AB AD interference to any situation where one item is used to cue another item. The basic idea is that with cued recall there will be an AB AD relationship involving some of the neurons or nodes making up the distributed representations of the studied items. The AB AD relationship produced by distributed representations will produce some level of associative interference or noise even when there is no obvious similarity between two or more cues. Thus, with a list of pairs the overlap between one cue and any other cue in the list is only likely to produce a small amount of noise, but small overlaps with all of the other cues in a list will produce more noise. The effects on recognition are similar. With both single item and associative recognition there will be some similarity in the representations of the words used on the study and test. Although similarity appears to be small, as the number of other items in the study list increases there will be an increase in both the hit rates, the false alarm rates, and the variances of these rates so discrimination will decrease. A similar argument applies to memories for complex events. That is, complex scenes and episodes contain observable features which also occur in other scenes or episodes. An AB AD relationship occurs if feature A becomes associated with feature B in one scene and with feature D in another scene.

As previously indicated Wixted (2004) argued against the importance that Underwood (1957) had assigned to PI and argued instead for the importance of a destructive form of RI. For Wixted, RI was based on mental activity but not on the similarity between the original and the interpolated items. It will be very difficult to distinguish between Wixted's version of RI and the version outlined above. However, we think that our version is to be preferred because it explains PI as well as RI and Wixted's version only explains RI.

In summary, the evidence indicates that associative interference via an AB AD relationship is pervasive and is a primary determinant of forgetting. The AB AD relationship

can occur at the level of the item as it does in paired-associate learning or in the recall of the sponsor of an event. It can occur with a contextual cue as such a cue will often subsume all of the items in a list or episode. It can also occur at the level of the observable features in a complex scene or episode, and it can occur at the level of the nodes or neurons which make up a distributed representation. However, the effects are somewhat different for hippocampal dependent and hippocampal independent memories. In addition, the effect of associative interference at some levels is moderated by context, with the ratio between inter-trial and retention intervals being a key determinant of the degree of forgetting observed. Associative interference also critically depends upon the retrieval operations involved in the memory task with recognition differing from recall. We also identified the disruption of context by either task demands or momentary lapses in attention as additional sources of forgetting.

Continuity between the short- and long-term domains: The short-term cued recall paradigm.

The previous sections address a number of issues primarily derived from sources outside the short-term memory domain. In this section we describe a short-term cued recall task that manipulates PI as a vehicle for describing how prior knowledge, cues, context and noise operate in the short-term memory domain. In the original version of the task (Tehan & Humphreys, 1995) participants study trials that consist of either one or two four-word blocks. In the two block trials, blocks are separated by an exclamation mark (!) at the end of the first block which signifies that the participant is to forget the block that they have just seen and to concentrate on remembering the four items in the next block as it is these items that are to be tested. At test, participants are presented with a category cue and are asked to recall the item from the most recent block that is an instance of the category (target). Proactive interference is manipulated on the two-block trials. On the no interference trials, the target is presented in

the second block among three unrelated filler items as the only member of the category in the trial. On the interference trials, in addition to the target in the second block, a second instance of the category is placed in the first, to-be-forgotten block among three filler items (e.g., the cue is *ANIMAL*, the target in the second block is *cat* and the foil in the first block is *dog*.) PI, due to the presence of another category member in the first block, can emerge either through depressed recall of the target item (*cat*), increased recall of the foil (*dog*), or both. In the early studies the category cue was presented either immediately after the last item in the second block or after a 2-second retention interval that was filled by participants verbally shadowing two four-digit strings.

The early studies (Tehan and Humphreys 1995, 1996) confirmed that when taxonomic categories were used performance on an immediate test was immune to PI in that there was no difference in target recall between the interference and control conditions and the interfering foil was rarely produced. In contrast after the two-second retention interval, target recall was depressed on the interference trials, and recall of the foil instead of the target was a frequent occurrence. However, when target and foil were rhymes and an ending cue was used (*hat* as foil, *cat* as target and *_AT* as cue), PI was observed on an immediate test as well as a delayed test. In addition, PI was observed on an immediate test with taxonomic cues if the two instances of the category rhymed (e.g. *cat* and *rat*). Tehan and Humphreys explained these results by appealing to the discriminative role that phonological codes play in the short-term domain. Their assumption was that phonological codes were available for the target item on an immediate test, but not on a delayed test. If that information discriminated between target and foil, as in the case of non-rhyming members of taxonomic categories, then immunity to PI would be observed on an immediate test. However, if the phonological codes did not discriminate PI would be observed on an immediate test.

Based on assumptions of distributed storage and superposition of memories, follow up studies (Tehan & Humphreys, 1998; Tolan & Tehan, 2002), tested the hypothesis that even with non-rhyming members of a taxonomic category PI could be observed on an immediate test if phonological codes for the foil could be provided by other items in the episode. If so, then phonological codes would be available that supported the target and other codes would be available for the foil thereby enhancing the competitiveness of the foil.

Tehan and Humphreys (1998; Tehan et al, 2004) demonstrated that phonological information for the foil could be provided by filler items in the list, down to the level where individual phonemes of filler items could support the foil (e.g *dart mop fig* in list 2 supporting *dog* in list 1). Tolan and Tehan (2002, Tehan et al, 2004) showed the same effects when phonologically related items to the foil were presented not in the list but in an unattended auditory stream under irrelevant speech conditions. Tehan and Humphreys labelled the impact of instances where phonological information was being provided by other items in the episode as item interactions.

Later studies using a variant of the cued recall paradigm, Humphreys et al. (2000) and Tehan et al. (2004) also examined target interaction effects and how they differed as a function of cued recall and free association instructions. In these studies the last item in the list was followed by a running memory span task in which the participants were required to recall the last three or four items in the list. The participants were informed that on some trials they would have to respond to a cue before recalling the final items from the list. One group was told to respond to the cue with the first word that came to mind that was semantically related to the cue (free association). The other group was told to use the cue to recall a semantically related word from the list (cued recall with an extra-list associate as a cue).

In Humphreys et al., (2000) recall performance was examined when two similar targets or two less similar targets were subsumed under the same cue. For example, for the cue *arts*, the two similar targets are *paint* and *painting* and the less similar targets are *painting* and *music*. The probability of recalling at least one of the two dissimilar targets was consistently less than predicted based on recall when only a single target was in the list. That is, the two dissimilar items mutually inhibited each other. This mutual inhibition did not occur with free association. The authors drew two conclusions from these findings. First that it ruled out a generate-recognize process where participants used semantic memory to generate a possible answer and then used episodic memory to confirm that the generated item had occurred in the study list. A generate-recognise process could be ruled out because it does not produce the mutual inhibition of two responses. Second, the findings indicate that the presence of a second target subsumed under the same cue did not play a special role in free association. When two similar targets were subsumed under the same cue there was no evidence for mutual inhibition. This suggests a role for context in cued recall but not free association.

Tehan et al. (2004) produced target interactions of phonological and semantic representations by including a phonological neighbour of the presented or not presented semantic target. For example, the target might be *wrench*, the cue *tool*, and the phonologically similar word *trench*. The presence of the phonological neighbour in the list without a target being present led to increased target intrusions (false memories of *wrench*) and also led to increased target recall when the target was present. This occurred with cued recall instructions but not with free association instructions. The failure to find any effect of the presence of a phonologically similar word on the production of the target with free association instructions shows that activation is not spreading from the phonologically similar word to the target. Thus, an explanation of these findings seems to require the use of a

contextual cue with cued recall instructions but not with free association instructions. In addition, there is no likely inferential process, given the experimental conditions, which would lead from the cue *tool*, to the knowledge that *trench* had been in the list, to the response *wrench*.

The first outcome of these cued recall studies highlights the importance of considerations about representations, specifically the binding of phonological and semantic representations, a process that started when young children began to name objects, and subsequently developed into hippocampus independent representations.

The second outcome of these cued recall studies indicated that PI and item interaction effects were cue specific. PI was only ever observed if the category cue subsumed both the target and the foil. In the case where a foil was *orange* and the target was *carrot*, PI was observed on a delayed test when the cue was *TYPE OF JUICE*, but not when the cue was *VEGETABLE* (Tehan & Humphreys, 1996). Likewise, Goh and Tan (2006) confirmed that target interaction effects only emerged if the target and foil were subsumed under the same cue. Not only is the specific category cue crucial to determining PI and item interaction effects, the prior studies showing that item interaction effects only occur in cued recall and not in free association (Humphreys, Tehan, O'Shea, & Bolland, 2000; Tehan et al., 2004) demonstrate the crucial role of the context cue. In short, recall in the short-term domain is jointly determined by context and cues that activate hippocampal independent memories.

A third relevant point that has not been mentioned as yet deals with our assertion that participants can bring the full range of hippocampus independent knowledge to recall. In the case of the cued recall task, it is well established that not all members of a category are equal, some category members are more closely associated with the category label than others and this is true for both taxonomic and word ending categories. In long-term cued recall with an extra-list associate or word ending cue dominant items of the category are better remembered

than the weaker members. Tehan and Humphreys (1996) demonstrated equivalent category dominance effects in the short-term cued recall task.

All the previous studies, plus the finding in Tehan et al (2004) that false memories for a specific item could be produced by the combination of a category cue and a rhyme of that item, provide strong evidence that STM is a reconstructive process where both pre-existing knowledge and contextual information can be combined. The same processes that are occurring in the long-term domain also appear to happen in the short-term domain.

There is also evidence for a changing temporal context in the short-term domain as there is in the long-term domain. That is, as previously noted an increase in the retention interval is known to increase interference from earlier lists in the Brown-Peterson paradigm (Loess & Waugh, 1967) and similar effects have been observed in the short-term cued recall paradigm (Humphreys & Tehan, 1992; Tehan & Humphreys; 1995). The two studies using variants on the short-term cued recall paradigm that also used a free association task (Humphreys et al., 2000; Tehan, et al., 2004) also provided support for an effect of disrupting context on retention. Although free association responses were somewhat faster than cued recall responses and the free association task was subjectively easier than the cued recall task, free association produced poorer running memory span performance than cued recall. The authors interpretation was that both cued recall and running memory span relied on a contextual cue but free association did not. Thus there was a greater disruption to the contextual cue relied on for running memory span when it was preceded by free association than when it was preceded by cued recall (see Farrell, 2012, for a similar argument comparing the effects of maintaining context versus disrupting context).

The role of articulatory/phonological information in the short-term cued recall paradigm is compatible with its ubiquitous role in the short-term domain. We will show shortly that at least some of the effects are also compatible with effects in the long-term

domain. The most important point here is that there are multiple sources of noise in the short-term domain which have to be taken into consideration in thinking about how fast forgetting occurs. In addition, the effects in the short-term domain seem to rely on the use of a contextual cue which strongly tie them to effects in the long-term domain. That is, the presence of a rhyme in the list enhances cued recall but not free association (Tehan, et al., 2004). This suggests that at least some of the words in the unattended speech which accompanies the presentation of the list also get associated with the list context as does some of the filler material activated during the retention interval. This is supported by Tolan and Tehan's (1999) results from exploring PI effects with different retention intervals and different study and retention interval modalities. However, having participants shadow digit strings means that context is also disrupted. In as yet unpublished work, the effects of a retention interval on item interaction effects is most pronounced in the transition from an immediate test to a 1-second distractor. Item interaction effects remained constant across 1 to 4 seconds of distractor activity. Thus, a filled retention interval appears to have two direct impacts, increasing the degree of noise and disrupting context. It also allows more time for recall to be disrupted via mind wandering

The final point that we would like to make is that the intersection process as a method of retrieval works equally well in the short-term domain as outlined in Humphreys, et al, (2000; Tehan & Humphreys, 1998; Tehan, et al., 2004). Thus, in the cued recall task the presentation of a category cue would elicit all the members of the category and would inhibit all other items. As the same time the context cue would elicit all items from the current list and inhibit all other items. What survives intersection are members of the category that were on list. Note that the intersection method provides a way of eliminating most of the influence of pre-existing knowledge yet provides a mechanism whereby hippocampus independent and hippocampus dependent memories can be combined.

Immunity to PI and STM Capacity

In the previous section we have presented our views on the commonalities between LTM and STM. However, to this point we have ignored other views of short-term memory and the issues that have traditionally been used in arguing for separate systems. We now turn to these issues.

Many of the early theories of STM (e.g., Atkinson & Shiffrin, 1968) proposed a hard capacity limit. This took the form of a specialised store or buffer that could hold a limited number of chunks. However, any attempt to measure the capacity of STM ran into difficulties due both to individual differences in capacity and to the difficulties in defining what was and was not a chunk. The assumption that LTM could contribute to performance in STM paradigms which followed on from Keppel and Underwood (1962) also complicated the search for a hard limit.

The assumption of a hard limit has been carried over into some modern theories (Cowan, 1995, 2000) as can be seen in Cowan's conceptualisation of the focus of attention. From his perspective four items/chunks can be held in the "focus of attention"¹². Importantly, in this model capacity constraints are associated with special retrieval dynamics, in that the items in the focus of attention are immediately accessible and do not need to be retrieved. In his words these items "are, in a sense, already retrieved; they reside in a limited-capacity store, eliminating the retrieval step in which PI arises" (Cowan, 2001, p. 103). Thus, Cowan argues that immunity to PI is a signature characteristic of a limited capacity store with immunity to PI being predicted with immediate tests of four item lists (or lower) and PI to be expected

¹² There is disagreement over the number of items which can be in the focus of attention. Cowan argued for four while McElree (2001) and Oberauer (2009) have argued for one. Loft et al. (in preparation) have looked at probe recognition for one-item (and longer) lists. They demonstrated that even the immediate recognition of an only item in a 1-item list was fallible and concluded that there is no evidence that a small subset of items can be held in a special state where they do not have to be retrieved.

with longer lists (see Halford, Maybery and Bain, 1988 and Wickens, Moody, & Dow, 1981 for evidence consistent with this position).

While immunity to PI with short-lists has since been replicated in diverse STM tasks (Halford, Maybery and Bain, 1988; Humphreys & Tehan, 1992; Tehan & Humphreys, 1995). Beaudry, Neath, Surprenant and Tehan (2014) in their review of short-term PI effects have pointed out that there are more studies showing the effects of PI on an immediate test with short lists, than studies showing immunity to PI. Moreover, we have consistently shown that PI and immunity to PI can be found in the same experiment whether it be short-term cued recall (Tehan & Humphreys, 1996; 1998) or immediate serial recall (Ralph et al., 2011). PI can be found with 3-word lists and immunity to PI can be found with 5-word lists, if the conditions are right (Ralph et al., 2011). Those conditions reflect the cues and codes involved, not the number of items that have to be remembered.

Those theories which do not assume a hard limit still assume that some distinctively STM structures or processes underlie a soft limit. For example, the capacity limit in Baddeley and Hitch's (1974) articulatory loop is the speed with which items can be rehearsed. This will vary with item characteristics and possibly with temporary states of the participant (e.g., alertness) so there is no hard limit. Similarly, Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, and Usher (2005) argue for a limited capacity buffer in accounting for differences between immediate, delayed and continuous distractor free recall. In their case capacity is limited by mutual inhibition among recently presented items leading to displacement of items from the buffer. Interestingly, in their simulations the capacity of this buffer emerged to be four words and was responsible for the observed immunity to PI in the recency portion of the immediate free recall curve. Note, however, that immunity to PI was observed only when recency items were recalled first where it is possible for phonological codes to provide discriminative information. When immediate free recall was constrained

such that participants recalled the initial list words first, PI was observed, an outcome that is consistent with the notion of output interference from the early items reducing the advantage provided by the phonological codes of the recency items. In short, immunity to PI of the recency items in immediate free recall could just as easily reflect the influence of the distinctiveness provided by recently acquired phonological codes,

It also seems possible to derive a soft capacity limit using only LTM structures and processes. For example, most current theories of immediate serial recall emphasize the role of bindings between position cues and the to-be-remembered items (see Hurlstone, Hitch, & Baddeley, 2014, for a review). Position cues have also played a major role in theories of serial learning (Johnson, 1991; Young, 1962). The basic idea behind both the STM and the LTM theories is that the cue for the n 'th position will be similar to the cues for the $n-1$ and the $n+1$ positions and that this similarity will decrease the further apart the two positions are. High levels of cue similarity produce multiple contenders for recall with high levels of response competition resulting in either increased order errors or mutual inhibition among items resulting in omission errors, in either case placing soft limits on what is recalled.

It also seems likely that other characteristics of the short-term paradigms will contribute to the limited capacity that is observed. For example, the short-term paradigms encourage or promote the use of phonological codes. That is, phonological codes are useful in short-term paradigms (Greene, 1989; Tolan & Tehan, 1999) and participants may prefer to use them (Logie, Della Salla, Laiacona, Chalmers, & Wynn, 1996). In addition, the rapid presentation rates used in STM paradigms may limit the ability to use anything but the most readily accessible memory codes. However, although the use of phonological codes and/or rehearsal is likely to reduce the possibility of disruption (e.g., loss of memory due to walking through a doorway) their use may also limit capacity. The high degree of similarity amongst the phonological codes would produce interference with recall which would increase as list

lengths increased. This soft capacity limit is at the heart of our explanations of immunity to PI for a small number of very recently presented items.

Decay and the role of item activation in memory access

The standard model of short-term memory as described by Nairne (2002) suggests that forgetting in the short-term domain involves the interaction of decay and activation. Decay and the enhancement of retrieval based on target activation offer the sharpest contrast with our ideas about a cue dependent memory and the importance of interference. However, it has been very difficult to test the distinction between decay and interference, a task that is made even more difficult if one accepts that mind wandering (disruption of context) is also a determinant of forgetting. Advocates of decay have to argue that if there is no source of interference there will still be forgetting. However, in order to observe forgetting these researchers need to prevent rehearsal and so they are required to either use a rehearsal preventing task that does not produce interference or to convince their participants not to rehearse/refresh during an unfilled or partially filled retention interval.

In contrast, advocates of interference have to show that there is no forgetting in the absence of interference. They have to worry about whether or not they have eliminated rehearsal and refreshment as explanations for the lack of forgetting. Refreshment is differentiated from rehearsal by the instructions given to the participant and by the pattern of neural activation involved (Raye, Johnson, Mitchell, Greene & Johnson, 2007). To further complicate matters some researchers have argued that refreshment is a much faster process than rehearsal (Barrouillet, Bernadin, & Camos, 2004). In spite of these difficulties, the evidence generally supports interference over decay (Lewandowsky et al., 2004; Lewandowsky et al., 2008; Waugh & Norman, 1965).

However, a rapid refreshment process cannot be ruled out due to the fact that in most STM paradigms the participant is motivated to rehearse or refresh the to-be-remembered

material. This has led to the use of paradigms where presumably this motive does not exist. For example, McKone (1998) looked at repetition priming in a lexical decision task. In two experiments she varied the interval between two presentations of the same word or non-word. She found strong evidence for interference and weaker evidence for decay. That is, the priming effect decreased with the number of words in the interval and with the amount of unfilled delay. However, forgetting could also have resulted from instances of mind wandering during the retention intervals (Berman et al., 2009).

In order to remove the motivation to rehearse or refresh, Berman et al. (2009) used a probe reaction time task where the negative probe used on trial n could come from trial $n-1$ or further back in the sequence. They were looking at the amount of interference caused by a recent negative probe as a function of the amount of unfilled delay between trial $n-1$ and trial n . Across seven experiments the only evidence they found for decay came from a combined analysis of all of the experiments which they suggested might have occurred due to mind wandering. However, they did not look at short delays less than three seconds. Campoy (2012) used a similar design and looked at shorter intervals. Campoy's two experiments involved a variable unfilled interval between the presentation of the interfering material and the to-be-remembered material (600, 1200, 1800, and 2400ms). This was followed by a 600ms presentation of the to-be-remembered material and a 400ms retention interval before the presentation of the probe. This study did find evidence for decay. However, because of the design we cannot tell whether any decay occurred during the 1000ms when the to-be-remembered material was studied and retained. In Experiment 1 the decay process asymptoted between 2200 and 2800ms (including the 1000ms at the end). In Experiment 2 it asymptoted between 1600 and 2200ms (including the 1000ms at the end).

The use of a free association task in the running span paradigm also provides evidence against decay and against a role for target activation in enhancing recall. Humphreys, et al.

(2000), referred to earlier, looked at both cued recall and free association and presented words at a 1-sec rate. The retrieval cue elicited the target in free association norms and was presented immediately after the last item in a 12 or 13 item list. In some lists a target was presented once. In other lists the target was repeated. In Experiments 1A and 1B the second presentation of a repeated target and the only presentation of a non-repeated target occurred in the same list position. There was no effect of repetition with free association instructions although there was a large effect with cued recall instructions. The lack of an effect of repetition on free association in the presence of a large effect in cued recall has also been confirmed in a more traditional paradigm (Nelson & Goodman, 2002). This pattern is also consistent with the theories of Cowan (1999) and Oberauer (2009), if it is assumed that an item in the focus of attention is maximally activated so that a repetition cannot further increase its activation. However, it is inconsistent with assumptions about activation in Reder et al. (2000) and Popov and Reder (2020).

However, in Experiment 1C (Tehan et al., 2004) there was no indication that there was any decay after a target should have been removed from a participant's focus of attention. In this experiment, when a single target was presented it was in position 3 in a 13-word list. If that word was repeated it was in position 8. Participants were told that this was a running memory span experiment and that the provision of the occasional cue was to make the running memory span task more difficult. They were instructed to recall the last three words in the list if the list stopped without the presentation of a cue, and if a cue was presented, they were to recall the last three words after responding to the cue. They were instructed to respond to the cue by producing the first related word that came to mind (free association). It thus seems reasonable that they would rehearse or pay attention to three words at a time, and after three words were in their rehearsal or attentional set, that they would drop rehearsing or paying attention to the oldest word when the next word was presented. This

means that they stopped rehearsing or paying attention to the word in position 3 when the word in position 7 was presented. Decay of position 3 can then have taken place over the course of the presentations in list positions 7 through 13. When the word is repeated in position 8 participants would stop paying attention when the word in position 12 was presented. This means that decay can occur over the course of two presentations (the words in positions 12 and 13). Unless all of the decay occurs in the first 2 seconds (two presentations) there should be more decay following the presentation of a single word in position 3 than following the repetition of that word in position 8. Thus, there should be some benefit due to repetition even if repetition does not directly increase the probability of free association as it does for cued recall. However, with free association in Experiment 1C a single target was produced 28% of the time and a repeated target was only produced 31% of the time. This is a very small difference especially considering the impact a repetition has on cued recall. In Experiment 1C with cued recall instructions a target presented once was recalled 16% of the time. When presented twice it was recalled 42% of the time. In short, whether target items were presented early in the list or late in the list, repetition effects were not strong in free association, a finding that is hard to reconcile with notions of decay of activation.

Tehan et al. (2004), also referred to earlier, provided further evidence against a role for target activation in enhancing recall. In Experiments 1 and 2 participants studied eight item lists along with some shorter and longer lists. When a target was present in an eight item list it was presented in position two or three. When a word which was phonologically similar to the target was present, it was in position eight. Both taxonomic and ending cues were used. The cue immediately followed the word in position eight. In this arrangement the presence of a phonologically similar word to the target enhanced target recall with cued recall instructions if the target was present and produced target intrusions if the target was absent. There was no effect on target recall or target intrusions with free association instructions.

Participants had been told that the primary purpose of the experiment was to measure running memory span and that the provision of a cue and their response to the cue was designed to interfere with running memory span. Thus, according to Cowan (1999) and Oberauer (2009), the LTM representation of the phonologically similar word in position 8 would have been in an active state due to its recency. This, however, was not enough to have an impact on free association.

In summary there is strong support for interference (not decay) over intervals relevant to what are commonly regarded as STM or working memory paradigms. However, Campoy (2012) has provided some evidence that decay is occurring at intervals shorter than about 3 seconds. This estimate of the time over which decay occurs is also consistent with our analysis of the absence of a repetition effect on free association in Humphreys et al. (2000). The Humphreys et al. (2000) analysis found no evidence for decay after two seconds but could not rule out decay occurring over intervals less than two seconds. Thus it is possible to talk about cues activating targets and to assume that the activation of the first item in a pair of lasts long enough for an association to be formed with the second item, without assuming that the activation lasts for more than two to three seconds and/or persists after the presentation of one or more items.

Articulatory/Phonological Codes in STM and LTM

The role of articulatory/phonological information versus the role of semantic information has long been assumed to distinguish STM and LTM. Conrad (1964) showed that the errors participants made in the immediate recall of short lists were similar to the acoustic confusion errors they made in identifying the same items. Furthermore, errors that are acoustically similar to the correct item occur frequently at short retention intervals, with the proportion declining toward chance as retention interval increased (Conrad, 1967; Estes, 1973). Phonological similarity also plays an important role, Baddeley (1966) demonstrated

that lists containing items with high levels of phonological overlap were not as well recalled as lists containing items with little phonological similarity. Similarly, Tell (1972) found that the phonological similarity effect has a significant influence on recall at a short retention interval, and practically no effect at longer retention intervals where the intervals were all under 10 seconds. Thus, the phonemic intrusion effect and the phonemic similarity effect are attenuated and finally eliminated as retention interval increases. Such is the robustness of these effects in the short-term domain, that phonological similarity has been identified as a “benchmark” finding that any model of STM should explain (Oberauer, et al, 2018).

These findings about the role of articulatory/phonological information and phonological similarity do indeed distinguish retention over short and long intervals but there are two problems with using them to argue for a separate STM system. One is that a fundamental characteristic of phonology guarantees a fast forgetting rate. The rate may be fast enough so that articulatory/phonological codes do not appear to be involved at long retention intervals unless certain structural conditions apply. That is, the importance of articulatory/phonological codes at short retention intervals is a property of those codes not a property of STM per se. The second is that there are differences within the short-term domain in how long these codes last suggesting that different types of memory are involved in the short-term domain.

Any theory of associative interference or similarity-based theory of forgetting should predict faster forgetting for articulatory/phonological information than for semantic information. There are 44 phonemes in English so they will be repeated in various combinations across the many items used in the typical STM experiment. In addition, several phonemes are confusable both in speech and at short-retention intervals (Conrad, 1964). In contrast, studies of list length effects in long-term recognition have shown that they are small and have led to the conclusion that words are not very similar to each other. In these studies

even the shortest lists are probably long enough, in conjunction with the interfering activity, to eliminate any articulatory/phonological effects so that the lack of a list length effect can be attributed to a low level of semantic similarity.

We have already shown that articulatory/phonological information can enhance interference and recall even when presented in a different word. In contrast, in recognition the articulatory/phonological information may have to be episodically bound to the lexical representation of the target word for the effects to be observed. Humphreys, Burt, and Lawrence (2001) used a delayed recognition task to investigate the processes that occurred in a priming task where participants named the target in the presence of a prime. In the priming task targets were either primed with a strong associate (prime = *doctor*, target = *nurse*), misprimed where the target was phonologically related to a strong associate of the prime (prime = *soil*, target = *dart*, strong associate of prime = *dirt*), or unprimed where the primed was unrelated to the target but a word which is phonologically similar to an associate of the prime was presented elsewhere in the list (prime = *length*, target = *honey* and prime = *office*, target = *witch*, unprimed associate of the prime = *width*). Note that in the case of the misprimed targets participants are presented with a prime (*soil*) that causes them to think of an associate of the prime (*dirt*) at approximately the same time they are pronouncing a word which is phonologically similar (*dart*) to the word they are thinking of. Thus, there is an opportunity to learn an episodic association between the word they think of and the information produced by reading/articulating the phonologically similar word. With unprimed targets they are primed with *length* which causes them to think of the associate *width*. At another point in the list they pronounce a word (*witch*) which is phonologically similar to the word they thought of. The important point is that these two events do not occur at nearly the same time so there is no possibility of learning an association of the word they think of and the information produced by reading/articulating the phonologically similar

word. The false alarms to *dirt* in the misprimed condition were greater than the false alarms to *width* in the unprimed condition, indicating a role for an episodic association between the word they thought of and the information produced by reading/articulating the phonologically similar word.

There is other evidence that shows that at times participants who are given instructions to recognize individual words in a pair base their recognition decisions on associative information such as a category label-instance association (Dennis & Chapman, 2010), a word-background picture association (Hockley, 2008), or a word-word association (Thomson, 1972). In these examples, performance on items which did not have an association with the other member of the pair was depressed (see Humphreys and Chalmers, 2016, for a more extensive discussion). If participants are basing their decision on an association between a lexical representation and a phonological representation it would explain why articulatory/phonological information can last for such a long time in some paradigms. In associative recognition interference comes primarily from the other items associated with one or the other of the pair members (Cohn & Moscovitch, 2007; Dyne, et al., 1990; Verde, 2004) not from the other pairs in the list (Kinnell & Dennis, 2012). Likewise, if you have stored a lexical-phonological association, other lexical-phonological associations in memory will produce an AB A'D relationship where A and A' are similar phonemes. This will interfere with recalling the lexical representation given the phonological representation as a cue. However, B and D are not similar because of the overall low level of similarity between the lexical representations. This lack of similarity between the lexical representations (B and D) implies that there will be less interference recalling the phonological information given the lexical representation as a cue, than recalling the lexical representation given the phonological representation as a cue (see Humphreys et al., 2020). In summary, the differences in the speed at which articulatory/phonological information loses its influence

across STM and LTM paradigms appears to be due to several factors not just the STM-LTM distinction per se. These factors include: a) the relative similarity of phonological and lexical representations, b) the nature of the bindings involved (e.g., is there an episodic association between the phonological and lexical representations?), and c) whether a phonological representation is being used to cue a lexical representation or whether a lexical representation is being used to recall a phonological representation.

However, the effects of reading an item aloud versus reading an item silently, is problematic for our account. For example, episodic recognition significantly improves for items read aloud (Bodner, Taikh, & Fawcett, 2014; Conway & Gathercole, 1987; Hopkins & Edwards, 1972; Humphreys, Li, Burt, & Loft, 2020; McLeod, Gopie, Hourihan, Neary, & Ozubko, 2010). In addition, reading items aloud also has effects in the cued recall paradigm. Tehan and Humphreys (1995, 1996, 1998) made two assumptions in order to explain why they only found evidence for PI on a delayed test when they cued with a semantic cue but found evidence for PI at both retention intervals when they cued with an ending cue. The first is that articulatory/phonological codes provide discriminative information on an immediate test when response competition is present. The second is that a feature of the memory system involved is that the effects of articulatory/phonological codes dissipate over a two second retention interval. A short-term cued recall study by Tolan and Tehan (1999) raises a problem with the second assumption. The problematic conditions in this experiment firstly involved conditions where participants read the items in the first block aloud and the items in the second block silently, and the retention interval varied between 1 and 8 seconds. Under these conditions the interfering item in block-1 was more likely to intrude, there was more interference with the recall of the target and this was true across all retention intervals¹³. The

¹³ This result is similar to the Tehan and Humphreys (1998) finding that inserting phonological information that is similar to the list-1 distractor increases the interfering effect of that distractor. However, the Tolan and Tehan

second problematic condition involved when the first block was read silently, the second block was read aloud, and the distractor activity was non-verbal. In this instance immunity to PI was observed at all retention intervals. These findings suggest that the memory for the articulatory/phonological information resulting from reading a word out loud can last much longer than the two seconds involved in producing the immunity to PI.

What Does Integrated Semantic/Episodic framework of LTM Allow Us to Conclude About STM?

In the short-term cued recall paradigm, when researchers cue with a taxonomic cue, they do observe immunity to PI on an immediate test but not on a test that is delayed by two seconds. However, with an ending cue PI at both retention intervals is observed. The same pattern occurs when we look at the cue dominance effect. Because the associates of a taxonomic cue are not generally phonologically similar it appears likely that there is a source of articulatory/phonological information which discriminates between the associates. This information would not discriminate between the associates of an ending cue because they are phonologically similar. However, when participants are asked to read a list of words aloud, this also results in the storage of articulatory/phonological information. The information produced by reading aloud appears to last longer than the information that produces the immunity to PI. It seems probable that the very short-lasting information cannot be explained by a theory of LTM. This conclusion is also compatible with Davelaar et al. (2005) observations about variables that affected short-term recency but not long-term recency.

If we do need to augment our theory of LTM, how do we conceptualize the augmentation? One possibility is to assume one of the traditional ideas about a short-term

(1999) finding shows that this is a retrieval effect not a discrimination effect because pronouncing words in list 1 and silently reading them in list 2 should have enhanced discrimination.

mnemonic system such as a special store or a state of activation. The problem here is that almost all of the evidence advanced over the years for such a store or state has either been shown to be inconclusive or more supportive of LTM involvement. The latest findings of this type are the findings in Loft et al. (in preparation) which show evidence that retrieving from a 1-item list is a fallible process. Our summary of results from the short-term cued recall paradigm also show that decay, and a role for item activation in the retrieval process, are unlikely processes save for at all but the shortest retention intervals. An alternative proposal is that there are systems that serve other functions but have mnemonic-like properties. As such, rather than viewing perceptual and motor processes as merely placing input and output constraints on a STM system, it is possible that STM phenomena are emergent properties of other systems (see Hughes, Chamberland, Tremblay, & Jones, 2016 ; Jones, Macken, & Nicholls, 2004, for examples) .

Perception, language processing and memory are typically described as separate processes that are underpinned by distinct brain regions. There are, however, multiple lines of evidence that brain regions that were classically defined as either perceptual or language systems are contributing to the encoding, maintenance and retrieval of mnemonic representations. For instance, single cell animal studies have shown that the visual cortex shows activity during retention intervals that is specific to the attributes of the maintained stimulus. More specifically, memory-delay related activity elicited by colour and motion has been recorded in areas V4 and MT respectively (Bisley, Zaksas, Droll, & Pasternak, 2004; Motter 1994). Human imaging studies have provided analogous results, indicating that delay-related activity in early perceptual areas carry information that reflect the physical properties of the stimuli (e.g. Baumann, Endestad, Magnussen, & Greenlee, 2008; Christophel, Hebart & Haynes, 2012; Harrison & Tong, 2009). Furthermore, human brain stimulation experiments have shown that the application of transcranial magnetic pulses over stimulus-

relevant perceptual areas during retention intervals interferes selectively with memory performance for associated stimulus attributes. For instance, stimulation of human areas MT has been shown to impair motion priming (Campana, Cowey, & Walsh, 2002). It is important to note that evidence for mnemonic representation of stimulus features in early perceptual areas is not restricted to the visual domain but that analogous findings have also been reported in the auditory (Gottlieb, Vaadia, & Abeles, 1989), and haptic domain (Koch & Fuster, 1989). Furthermore, EEG evidence suggests that in addition to high-fidelity perceptual representations in sensory areas, shared abstract (or scalar) representations of stimulus attributes such as frequency, duration and intensity are also decodable from prefrontal areas (c.f. Bancroft, Hockley, & Servos, 2014). However, given that EEG does not offer a sufficient spatial resolution, testing this hypothesis will require single-cell recordings. If these findings can be confirmed it will show that there is a capacity to store common aspects of sensory signals from different modalities. Such a system is more general than systems representing specific aspects of a given modality, but are not as general as the dedicated short term systems which have dominated the STM literature.

Analogous to the role of early perceptual areas in the maintenance of elementary sensory stimulus features, brain regions typically associated with the perception and generation of language have also been implicated in the maintenance of speech stimuli. Converging evidence from human imaging (Awh, Smith, & Jonides, 1995; Henson, Hartley, Burgess, Hitch, & Flude, 2003; Paulesu, Frith, & Frackowiak, 1993), brain stimulation (Romero, Walsh & Papagno, 2006) and lesion studies (see Vallar & Papagno, 2002 for an overview) has shown that the left frontal operculum (Broca's area) and the left inferior parietal lobule underlie storage and rehearsal processes for verbal material. More specifically, it has been proposed that the left frontal operculum serves as a phonological output buffer, while the left parietal cortex serves as an input buffer (Catani, Jones, & Ffichte, 2005; also see Howard &

Franklin, 1987; Monsell, 1987; Papagano et al., 2017) linking inner or covert speech with rehearsal.¹⁴

However, maintaining verbal material may not be the primary function of inner speech. It has been proposed that inner speech may enable the online correction of memory errors (for a review see Perrone-Bertolotti, Rapin, Lachaux, Baciú, & Loevenbruck, 2014). Skipper, van Wassenhove, Nusbaum, and Small (2007) have also proposed that it might be responsible for integrating information derived from lip movements with information derived from the speech signal. This integration is revealed in the McGurk effect (McGurk & MacDonald, 1976), where simultaneously hearing a spoken word and seeing the lip movements associated with speaking a different word, can produce the illusion of hearing a third word. Jordan and Rumelhart (1992) were not concerned with inner speech but instead the problems caused for learning when feedback about the success or failure of a behaviour such as shooting a basket in basketball occurred in a different modality (e.g., visual) than the control system (e.g., motor control) which produced the behaviour. Their proposed solution was to take the control settings and use them to predict the feedback which would occur in the other modality. Then the discrepancy between the observed feedback and the predicted feedback could be used to adjust the control settings to reduce the discrepancy on the next trial. When this idea is applied to inner speech it suggests that a principle function might be in a child's learning to adjust the articulators in order to reproduce the speech sounds the child hears in the environment when learning to talk. It has been also suggested that a rehearsal processes based on inner speech may have very different forgetting characteristics than those in LTM. For instance, mere task-irrelevant engagement of articulatory processes is generally deemed to be sufficient for articulatory suppression to have its effect on processing (e.g. Baddeley, 1990).

¹⁴ Broca's area has also been found active in discrimination tasks involving non-verbal rhythmic auditory stimuli (Platel et al, 1997; Baumann, Vromen, Cheung et al., 2018), suggesting that its mnemonic involvement is not restricted to speech material.

At this time there is probably no way to decide amongst these competing ideas about the role of inner speech due to the behavioural and neurological complexity involved. Skipper, Devlin, and Lametti (2017) reviewed neuroimaging and other neurologically focussed methods. They concluded that although motor areas were clearly involved in speech perception, no simple network model would suffice.

This brief summary illustrates that brain systems, classically labelled as perceptual and language systems, are contributing to memory maintenance. These are not specialized STM processes, but they can explain preserved performance of patients with damage in classical mnemonic areas, such as the hippocampus. Importantly, however, even though these perceptual areas are typically conceptualised as short-term buffers, a large number of delayed-discrimination experiments have shown that stimulus features are extremely well retained over time-scales that go beyond those classically associated with STM stores. For instance, delayed discrimination of features such as spatial frequency, speed, orientation and colour is as precise at delays of 10-60 seconds as during simultaneous discrimination (for an overview see Magnussen & Greenlee, 1999). Most impressively, later single-trial studies have shown perfect preservation of visual spatial frequency at 50-hours retention intervals, (Magnussen & Dyrnes, 1994; Magnussen, Greenlee, Aslaksen, & Kildebo, 2003), suggesting a mnemonic role of perceptual systems beyond short-term maintenance.

It is our contention that the existence of a powerful theory of LTM coupled with the existence of sensory and language-based systems, which also serve a mnemonic function, means that the traditional ideas about special stores or states of activation are probably superfluous. This means that there will probably not be any overall accurate theory developed about how LTM interacts with STM. Instead there will be specific theories developed that describe how specialized perceptual and linguistic systems which have mnemonic properties interact with LTM. Our contribution has been to advance several principles about how LTM

works. We anticipate that these principles will provide substantial constraints on how LTM can interact with these specialized perceptual and linguistic systems. In the next section we defend our approach as at least being in the right direction.

Is Our Integrated Semantic/Episodic Framework Explanation of Retention Over Short Intervals Going in the Right Direction?

We are at the early stages of creating a comprehensive theory of LTM and STM. At this stage all we wish to claim is that we are going in the right direction. We believe that we have made a strong argument for including both episodic and semantic memory in attempting to explain retention over short intervals, as well as contributions from perceptual and language based systems which have a mnemonic function.

We have divided the argument into two parts. In the first part we looked at structural issues and computational constraints. We do not think that one can have an adequate theory of memory without having a theory of representations. We have used ideas about articulatory/phonological representations and more abstract representations to explain a variety of findings in both the short-term and long-term domains (also see Humphreys et al., 2020). A more complete explanation about where those representations come from can be found in Humphreys and Hannah (under revision). We believe that our computational constraints on extracting and using knowledge from semantic memory and avoiding massive interference in other situations are sound, though they can be implemented in a number of different ways. The ideas about how the hippocampus interacts with the cortex in storing new memories is more speculative. However, a theory about how hippocampus and cortex work together seems essential if we are to make any headway on explaining how information about the order of words in a sentence and the order of phonemes in a word, as well as information found in faces and scenes, can have such a profound effect on new learning.

The second part of the argument relied on relatively generic assumptions about parallel processing and distributed representations. It also relied on the principles proposed by Surprenant and Neath (2009). We think that our explanation provided below as to how we have gone beyond previous work in addressing those issues/principles will help in deciding whether we are going in the right direction.

Our approach emphasizes the role of cues in memory. The notion that STM is cue-driven is not entirely new although very rarely explicitly addressed. For instance, in most computational models of immediate serial recall, some form of position cue is used to interrogate memory, or alternatively in chaining models of serial and free recall a list item serves as a cue for the next item in a list (see Hurlstone, Hitch, & Baddeley, 2014, for a discussion of how order is represented in short-term memory). Likewise, in models of serial and free recall, start and ending cues are frequently proposed (Farrell, 2012; Henson, 1998). The role of list context could be seen in Henson's analysis of intrusions from prior lists into the current list (Henson, 1998) and a list cue is an essential component of Farrell's (2012) model of grouping effects in episodic memory. Oberauer's (2009) version of the embedded process model also involves the binding of activated representations to context in a cue-like cognitive coordinate system. While there has been a general trend toward implicitly talking about the role of cues in STM, there is no systematic approach to what cues are involved, or how those cues are used. We go beyond most examinations of retention over short intervals by an extensive discussion of results from the short-term cued recall paradigm precisely because it allows cues to be manipulated. This paradigm clearly illustrates the need to consider semantic, part-word, and contextual cues in explanations of retention over these short intervals. Other ways we go beyond most of the existing literature is in our ideas about how phonological representations of a word can cue a more abstract representation of that word and even enter into an episodic association with the more abstract representation.

We have also considered the question of how information from two different sources or systems is combined. The traditional answer about combining information from STM and LTM has been that one attempts recall from STM and if that fails one attempts to recall from LTM. However, the phonological information that results from reading a word out loud enhances the probability that a response that is consistent with the information will emerge into consciousness (Tolan & Tehan, 1999). The complex pattern of results we have reviewed involving cued recall and free association is also supportive of a system whereby different sources of information constrain the response which emerges into consciousness. Our conclusion is that thinking of a parallel system involving multiple constraints is a better way to think about the integration of LTM and STM than recalling from one system or the other.

Our modern account of associative interference constitutes a strong endorsement of the cue overload principle. Our approach differs from traditional ideas about associative interference in our treatment of context, our explanation as to how observable features in complex scenes or episodes can enter into AB AD relationships, and our explanation about how distributed representations permit many items in memory to contribute small amounts of noise.

Our insistence that both episodic memory and retention over short intervals must make use of information about how words are ordered in sentences, how phonemes are ordered in words, and how the parts of a human face and the component parts of scenes are arranged, are in accord with the reconstruction principle. The demonstration that a false memory for a specific target word can be created out of the lexical information activated by the cue, and the phonological information contained in specific filler items in the study list that are activated by a context cue (Tehan et al. 2004), is a dramatic illustration of the power of reconstruction.

Surprenant and Neath (2009) talked about the importance of relative discriminability and discussed discrimination problems where items differed on a single dimension. We tend to talk about noise, by which we mean anything that makes the discrimination problem more difficult (Humphreys & Chalmers, 2016). The two constructs are closely related and we see their inclusion in any account of human memory as essential. Note, however, that the identification of the noise may vary depending on whether distributed or local representations are assumed and with other theoretical distinctions.

We also endorsed the idea that representations can enter into associations with incoming stimuli and with other representations. This is based in part on research showing that rats and young children can form an association with a memory which then transfers to the stimulus which gave rise to that memory (Humphreys & Hannah, under revision). These representations would be considered as being sensory/motor or embodied representations, but Humphreys and Hannah also argued for the existence of more abstract representations. Humphreys et al. (2020) also argued that the representations used in memory were closely linked to the representations assumed in the reading and language production literatures (Levelt, et al., 1999; Oppenheim, et al., 2010; Perfetti, 1992; Perfetti & Hart, 2002; Plaut, McClelland, et al., 1996). This idea is also an integral part of the psycholinguistic theories of STM (R.C. Martin, et al., 1999; N. Martin & Gupta, 2004). We are not arguing that the use of abstract representations is a feature of all forms of human memory, but they seem to be an integral part of the memories for words over both short and long retention intervals.

We started this article with the recognition that dividing memory into discrete entities has become problematic in that no memory task is “process pure”. We are not the first to address the overlap between STM and LTM, or STM with semantic memory. However, we think this article adds to the literature in two significant ways. Firstly, it addresses often ignored issue of how semantic and episodic memory interact. Secondly, by approaching STM

from the perspective of long-term episodic memory an alternative frame of reference is available for researchers to evaluate and interpret memory performance over the short term.

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