Review: Recent Developments in Global Matching Models of Episodic Memory
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RECENT DEVELOPMENTS IN GLOBAL MATCHING MODELS OF EPISODIC MEMORY

A Partial Review of Cognitive Modeling in Perception and Memory: A Festschrift for Richard M. Shiffrin

Edited by Jeroen G. W. Raaijmakers, Amy H. Criss, Robert L. Goldstone, Robert M. Nosofsky, and Mark Steyvers. New York, NY: Psychology Press, 2015. 302 pp. Hardcover, $160.

In May 2013, family, friends, a mentor, former students, and colleagues gathered in Bloomington, Indiana, to celebrate the career of Richard (Rich) M. Shiffrin. It was the hottest ticket in town, and one of largest venues on the Indiana University campus was filled to capacity. Personal stories of Shiffrin's influence and friendship were conveyed, and a series of research presentations was made. *Cognitive Modeling in Perception and Memory* is a compendium of some of the research that was presented. The topics covered in the Festschrift are a testament to breadth of the contribution Shiffrin has made to the fields of cognitive psychology and mathematical psychology. Here, I provide a review of the chapters comprising the section on episodic memory while trying to place this research in the context of Shiffrin's research program.

The hallmark of Shiffrin's research program is its interaction of theory and data in order to build better accounts of the phenomena that characterize human memory and perception, and he has duly received accolades for it. On the other hand, we sometimes hear at meetings that formal models, like those created by Shiffrin and his colleagues, "can predict anything." It might therefore surprise the reader of his Festschrift that in my work with Shiffrin we explored many models that did not explain the data of interest for every model we found that does. Indeed, Shiffrin, his students, and his colleagues have learned as much about memory and perception from the failures of various models than from their successes. Of course, the sufficiency of a model does not directly imply its necessity, and Shiffrin has told me many times that the models he and his colleagues have created over the years are certainly wrong and gross approximations to human memory and perception at best.

One of the most remarkable of Shiffrin's talents is his ability to identify the aspects of the theory that need attention and the models that are most important to develop and test. Importantly, the models are described in concrete terms, and therefore the behavior of the models can be objectively determined. Shiffrin's models of visual search, word identification, and episodic memory are noteworthy for the parametric predictions they make. Perhaps for this reason, Shiffrin, his colleagues, and many in the research community have tested the models in many different ways, and when the data challenge the models, unsuccessful or inadequate versions of the models are updated in favor of new models that provide more successful or comprehensive accounts of memory and perception phenomena.

Some of the most interesting problems are not really problems, though; these quasi-problems are holes in our understanding that result from the fact that the theory has not been extended to account for a particular phenomenon. There are many holes in the theory. Shiffrin understands this, of course. One of my first memories of working with Shiffrin is of him telling me with great exuberance, "We need more models! We need more models!" This Festschrift describes a few.

The section on episodic memory highlights Shiffrin's memory theory. From the Atkinson–Shiffrin buffer models to the search of associative memory (SAM) models to the retrieving effectively from memory (REM) models, a small number of assumptions are threads that run through the development of this theory and hold it together. One thread concerns the nature of retrieval. Shiffrin's models are known as global matching models because the images or traces representing a large number of events influence the retrieval of the memory image of a target event. This assumption of global matching models distinguishes them from local access models that assume that only the state of the target image influences its retrieval. The nontarget images cause a significant amount of interference via retrieval competition in global matching models, especially when they are similar to the target image, and this is one source of forgetting. Another source of forgetting is the difficulty in reinstating the mental context in which an event occurred (Mensink & Raaijmakers, 1988). However, according to the global matching theory, forgetting is not the result of the inhibition of memory images according to these models.

The chapter by H. L. Roediger and J. F. Nestojko identifies a hole in the global matching theory that existed for many years, accounting for the effects of memory testing. More specifically, Roediger and Nestojko note that "learning has been studied for 130 years and yet only a handful of experiments have dealt with the fundamental question of the relative roles that study and test events play in the process" (p. 109). When devising a model, the first step is to obtain relevant data, and most of these investigations have been conducted in the last few years. A key finding is that memory testing leads to a lower rate of forgetting than studying when retention is measured via recall (Roediger & Karpicke, 2006). The "testing effect" is so important because in these 130 or so years of memory research only a small handful of factors have been discovered that reduce the rate of forgetting.

Roediger and Nestojko point out that Raaijmakers and Shiffrin (1981) anticipated these developments, and they relate their findings to the global matching models. For instance, they claim that one way of looking at their recent data indicates that the benefits of testing are about 2.5 times greater than benefits derived from simply studying. To the extent that retrieval involves the encoding of additional information above and beyond that of study, the general result seems to have been predicted by Atkinson and Shiffrin in 1968: "When the subject is concentrating on rehearsal, the information transferred would be in a relatively weak state and easily subject to interference. On the other hand, the subject may divert his effort from rehearsal to various encoding operations which will increase the strength of the stored information" (p. 115). Such encoding operations may develop new associations between items or focus encoding on specific aspects of an item. But perhaps the most effective encoding operations or control processes involve the retrieval of the desired memory image, and perhaps students who use flashcards to prepare for exams have implicitly believed in the utility of this control process for a long time.

However, research is never simple. Testing memory has both benefits and costs, and the benefits depend on the manner in which retention is measured (Malmberg, Lehman, Annis, Criss, & Shiffrin, 2014, for a review). In addition, it would be highly desirable to specify in concrete terms why the benefits of testing occur. This is a goal of the chapter by D. E. Huber, T. D. Tomlinson, Y. Jang, and W. J. Hopper. They first ask why retrieval of some items from a list impairs memory for other items. Under conditions in which a common cue is used to probe memory, such findings are predicted on the assumption that retrieval practice strengthens the cue–target association in memory, and these images increase the amount of interference during the retrieval of subsequent items. However, when independent cues are assumed, accounting for the costs of retrieval practice is much more of a challenge. For instance, other SAM and REM models can account for phenomena suggestive of inhibition, such as positive list strength effects, intentional forgetting, and retrieval practice effects (Lehman & Malmberg, 2009; Malmberg & Shiffrin, 2005; Raaijmakers & Jakab, 2013), but Huber et al.'s model of the effect of retrieval practice with independent cues is remarkably elegant because the SAM with Recovery Interference (SAM-RI) model accounts for a slew of new findings by introducing one simple assumption.

A key assumption of the SAM and REM theory is that retrieval during the performance recall tasks (e.g., cued, free, serial) is accomplished by stochastically sampling images from memory and then attempting to recover the information stored in the sampled image. According to many prior models, the competition between images to be sampled was the source of interference and forgetting. Failure to recover the contents of images is akin to having the contents of an image on the tip of your tongue (Brown & McNeil, 1966). The original formulation of the SAM model predicted a correlation between the tendency to sample a given image and to successfully recover the information from it. However, Huber et al. noted that "Raaijmakers and Shiffrin (1981) realized that other tasks and situations might decouple the sampling and recovery strengths" (p. 84). According to the SAM-RI model, retrieval improves the ability to recover information stored in memory to a greater extent than it affects the ability to sample an image because successful retrieval creates a new, strong association between the target trace and reproduction of its contents. In addition, delays in testing create the possibility for a more diverse set of contextual cues to be used to probe memory. Therefore, some images that were not initially recovered may be recovered later. Accordingly, previously retrieved images are more resistant to forgetting than images that have not been previously retrieved.

Huber et al.'s results are noteworthy for three reasons. First, some of the very findings Huber et al. show that SAM predicts are findings have been used to criticize global matching models by those who advocate theories that assume that strengthening memory images must also inhibit other memory images (Anderson & Bjork, 1994). The debate between global matching models and inhibition models has been heating up for some time, but Huber et al.'s contribution shows that that inhibition-like effects are not inconsistent with the global matching framework, which does not assume inhibition. Second, their models are important to understanding phenomena that may be important to understanding and improving everyday learning in scholastic settings. Third, the models developed by Huber et al. are excellent examples of the type of research Shiffrin has conducted for many years.

An underappreciated aspect of Shiffrin's research program is that models developed within the Atkinson and Shiffrin framework are the result of careful task analysis, like that advocated by Crowder (1976). The models must be tailored to be consistent with the experimental designs used to gather data. The main challenge for the researcher is develop these models in a manner that is consistent with the general theoretical framework and with the assumptions made in other models developed to account for the results obtained from similar experimental designs. Having established that decoupling the sampling and recovery processes can account for some inhibition-like phenomena, the main challenge for Huber et al. is to develop a principled formulation of how and when the sampling and recovery processes of global matching models are or are not decoupled and the consequences of these assumptions for understanding of phenomena to which earlier SAM models were applied.

Although differentiation was introduced to global matching models by Shiffrin, Ratcliff, and Clark (1990) 25 years ago, the chapter by Criss and Koop is timely on this anniversary and highlights several years of programmatic research. The differentiation mechanism in the global matching models is not widely known, and this is unfortunate because it is rare that a new thread critical to holding together the global matching models is created. Before the introduction of differentiation, it was assumed that increasing the amount of time an item was studied simply added information to memory about the item, the context in which it was encountered, and the other items rehearsed with it. Repetitions of an item were thought to add a new image of the item to memory. In this sense, increases in study time and repetitions strengthened the representation of the item in memory. In light of this simplistic assumption, it is interesting to note that Shiffrin once told me that the he thought the reason that people liked his models is that they are based on obvious assumptions, but here is one case that an obvious assumption was wrong. The problem was that the early global matching models predicted that strong images in memory would cause more interference than weak traces in memory when tested via item recognition, but after perhaps a dozen experiments, Shiffrin and his colleagues were able to disconfirm this prediction.

Differentiation was a mechanism proposed to reduce the interference that results from improving the encoding of an event in memory. Differentiation is rooted by the assumption that memory images are multidimensional. They consist of sets of features represent various aspects of events, just as one's curriculum vitae represents different aspects of one's career. Adding more information about an event to an image differentiates or makes that image of the event less similar (on average) to images of other events in addition to strengthening it. Global matching models in the REM family assume multidimensional representations and differentiation, and they are able to account for a host of findings based on these simple assumptions that prior global matching models could not. In hindsight, this too is an obvious assumption given prior research in areas as diverse as perceptual learning and expertise, but complications to the models are never formally introduced unless the data demand them.

Criss and Koop present the basic finding attributable to differentiation according to global matching models: the strength-based mirror effect. A mirror effect is observed in recognition testing when an operation produces greater accuracy via greater hit rates and lower false alarm rates. For instance, increasing the number of times or the amount of time stimuli are studied produces a mirror effect when strength is manipulated between lists. Prior global matching models predicted that the strength of unstudied items would be unaffected by the strength of the items that were studied. Hence, they failed to predict the false alarm rate aspect of the mirror effect, based on the effect encoding has on memory. For this reason, a somewhat awkward workaround accounted for the strength-based mirror effect: Subjects were assumed to be more biased to endorse a foil when weak items were studied than when stronger items were studied (Gillund & Shiffrin, 1984). However, when differentiation was introduced in the REM family of models, the strength-based mirror effect was naturally predicted because stronger, more complete memory images were less similar to the representations of random unstudied stimuli than weaker, less complete images. For this reason, false alarm rates are predicted to be lower as more information is encoded in the memory images of targets.

Despite the ease with which differentiation accounts for the strength-based mirror effect, it is still possible that a response bias, as in signal detection theory, also plays a role. Indeed, some researchers claimed that there was no empirical justification for differentiation. Criss and Koop review the results of several experiments that produced strength-based mirror effects but failed to find evidence for shifts in bias when the strength of studied items was manipulated. These findings are inconsistent with the hypothesis that response bias is affected by composition of the study list. Another version of the bias account of the strength-based mirror effect states that the composition of the test is what determines the level of response bias, but the only experiments in which strength-based mirror effects and shifts in response bias occur are those that warn or inform the subject that only strong or weak stimuli will be tested. Importantly, in the absence of such warning, the strength-based mirror effect is observed. In addition, Criss and Koop report further support for the differentiation models based on reaction time analyses, electroencephalographic recordings, and functional magnetic resonance imaging.

In their chapter honoring the contributions of Shiffrin to our understanding of episodic memory, A. Osth and S. Dennis set forth an agenda for providing a new "unified" model of episodic memory. Such theories are sometimes called global memory theories, and they are implemented in formal models that explain a diverse set of observations with a minimal number of basic assumptions. J. R. Anderson's Atomic Components of Thought theory, Estes's array theory, and Murdock's (1997) theory of distributed associative memory (TODAM) are examples of global memory theories. Regardless of the specifics of the different theories, the advantage of global memory modeling is that the results of a variety of experiments are explained within a consistent theoretical framework.

One of the best examples is the SAM family models of the retrieval processes used to perform free recall, cued recall, and recognition (Gillund & Shiffrin, 1984). The basic assumptions of the Atkinson and Shiffrin family of models were inherited by the SAM family of models, allowing the next generation of more detailed models to account for the findings relevant to the older generation of models in addition to expanding the scope of the theory. The REM family of models in turn inherited the SAM generations' critical assumptions and combined them with new assumptions about multidimensional representations and the relationship between episodic memory and lexical/semantic memory in order to relate the theory to a wide variety of empirical manipulations in experiments from free recall, cued recall, source memory, item recognition, associative recognition, plurality discrimination, lexical decision, and perceptual identification.

In light of the several existing global memory theories, it is somewhat surprising that Osth and Dennis claim that recent memory research has focused too narrowly on understanding how specific memory tasks are performed. Osth and Dennis specifically suggest that the SAM and REM family of models may not be able to account for new findings about the order in which items are freely recalled. However, SAM and REM models account for all known, important contiguity effects, including the effects of continuous distraction on free recall (Lehman & Malmberg, 2013). In addition, recent evidence demonstrates a role for control processes in producing contiguity effects and implicates the role of privileged memory representations like those often assumed to reside in short-term or working memory (Lehman & Malmberg, 2013). These findings are not predicted by the temporal context models described by Osth and Dennis on the assumption that there exists no short-term memory that plays a role in recency, contiguity, or the order in which items are recalled.

Osth and Dennis also note that an account for serial recall has been missing in global memory theories, "Of all the global memory models, only the TODAM model was applied to serial recall" (p. 132). Setting aside the fact that this statement ignores the contribution of models of serial recall developed by J. R. Anderson (Anderson, Bothell, Lebiere, & Matessa, 1998), Lee and Estes (1977), and, indeed, Shiffrin and Cook (1978), it is worth considering in the context of these chapters honoring Shiffrin contributions whether the important findings described by Osth and Dennis are amenable to the SAM and REM theory.

The jumping-off points of their proposal are two assumptions consistent with the findings and conclusions of Shiffrin and Cook (and others); there appears to be information used to perform serial recall that represents the occurrence of the item and information that represents its position on a list. The assumption that item information is important for serial recall is beyond dispute, and it also clear that associations created between the items are also important (see Crowder, 1976, for a review). Osth and Dennis cite one finding that implicates positional information in serial recall. When a series of serial recall trials are performed, erroneous extralist intrusions from items studied on prior lists to subsequent lists are to nonrandom serial positions (Henson, 1996, 1998). Items studied and recalled on earlier trials tend to be output in the same (or nearly the same) serial position as they appeared in the earlier list.

It is important to note that the phenomenon in extralist intrusions is not as orderly as stated because it is rare for these extralist intrusions to occur (Henson, 1998; Lehman & Malmberg, 2009). Within-list transpositions of items are much more likely to be the source of an error in serial recall, as are omissions (Henson, 1998). In addition, extralist intrusions are far more likely to occur when the intertrial interval is short (e.g., less than 4 s), and items from the initial and final serial positions are more likely to intrude than items from middle serial position (Henson, 1998). These findings suggest that temporal context plays a role in the extralist intrusions.

Assumptions consistent with these findings are incorporated into models, such as SAM and REM, that assume item representations, interitem associations, and item–context associations are encoded in memory. Item and interitem associations represent the occurrence of the item, and the item–context association represents the relative time or position of the item on the list (Estes, 1955; Lehman & Malmberg, 2009, 2013; Mensink & Raaijmakers, 1988). Such models typically assume that temporal context changes slowly and randomly within a list and more quickly between lists. Thus, changes in temporal context would account for why extralist intrusions decrease dramatically with increases in the interlist retention interval.

Shiffrin and Cook (1978) proposed that serial recall, especially with unfilled retention intervals, is based on a combination of retrieval from short-term and long-term memory. They found that serial recall accuracy diminished dramatically when the retention interval was filled with the performance of an arithmetic task (cf. Glanzer & Cunitz, 1968). The implication is that it is possible that at longer retention intervals serial recall is increasingly likely to be based on retrieval from long-term memory, and at short retention intervals retrieval is based on the items current being rehearsed.

To account for the nonrandom nature of interlist intrusions, a simple extension of the SAM and REM temporal context assumption may state that nonrandom changes in temporal context are correlated with serial position. A model such as this would handle the issue of nonrandom extralist intrusions on the further assumption that temporal context information was used to cue memory when an item from the current list is not available. Note that an error of omission in the correct serial position must occur because the nonrecalled item from the current list was weakly encoded. For instance, if an item from a certain serial position on the current list was not rehearsed, then it would also be unlikely to be well encoded in long-term memory. This is most likely to occur for the last item of the list because rehearsal and encoding of that item is disrupted by the initiation of free recall. Use of nonrandom temporal context information cue would make an item from the same serial position on earlier list more likely to be retrieved from long-term memory, especially at short retention intervals. These assumptions and the seemingly indisputable assumption that earlier list items are likely to have been output already makes the last item on the list a most likely candidate for an extralist intrusion.

At this point, this proposal to account for some aspects of serial recall constitutes nothing more than a few scribbles on the back of an envelope (but see Lehman & Malmberg, 2013, for further discussion). However, this is as good an opportunity as any to note that holes in Shiffrin's theory are not necessarily indicative of a problem; they are often simply a reflection of the extent of human memory and perception and one human's limited capacity to process information.

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GODLY AND GODLESS MORALITY

The Bonobo and the Atheist. In Search of Humanism Among the Primates

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What do bonobos and atheists have in common? Neither believes in God, but for different reasons. Whereas *Homo sapiens* live in a symbolic niche com-