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# Exploring the possible and necessary in working memory development

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**COMMENTARY**


**Exploring the Possible and Necessary in Working Memory Development**

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**Abstract**

This commentary considers Simmering's monograph on a dynamic-systems theoretical approach to understanding working memory development, with reference to the past, present, and future. In the section on the past, I attempt to provide a further historical context for the work, discussing from where it stemmed and how it is unique. In a second section I contemplate the purpose of the present modeling. The aim of the monograph may be primarily to establish a simple possible account of development based on neural connection strength and dynamic principles; it should not be judged as a proposal of what is necessarily true. Finally, in the section on the future, I suggest some phenomena that dissociate performance levels from stability over time and therefore appear to require modifications of the theory. Several suggestions are made as to where further refinement of the modeling effort could lead.

**Exploring the Possible and Necessary in Working Memory Development**

Upon my arrival at the University of Missouri, where I have worked for most of my career, I was assigned to a laboratory recently vacated by Esther Thelen, a foremother of the present-day interest in dynamic systems theory as applied to child development. When Esther moved out of her infant-stepping lab, she left attached to the door one of my favorite cartoons, which I have since misplaced but have thought of often. It featured a beaver talking to another animal, with an enormous hydroelectric dam in the background. Of this structure the beaver remarked, "Well, I didn't actually build it, but it was based on my ideas." The dynamic systems modeling of processes underlying working memory from infancy through childhood in the present monograph by Simmering might be viewed as a hydroelectric version of earlier beaver dams. My contribution is to comment on how the dam is related to past work (the history), how well it is operating (the modeling), and where we might go from here (the persistent questions).

**The Past: A Little History**

As series of important beaver dams, first there are the empirical phenomena. Working memory is a critical process in human cognition, representing the small amount of information that can be held in mind and used in the service of many processes: remembering the early part of a sentence long enough to integrate it with what comes later, carrying a digit when doing mental addition, using mental imagery to rotate puzzle pieces to see which ones might fit together or, in an infant, perhaps comparing a babbled utterance to an adult model or retaining memory of Mom as she disappears behind a door. The study of working memory may be as old as the study of memory generally. Ebbinghaus (1885/1913) is typically credited with initiating the scientific study of memory, in his groundbreaking research in which he repeatedly tested

himself until he learned series of nonsense syllables. What is germane here is his finding that, although a list of 12 syllables could be learned only after 16 repetitions, a shorter list of 7 syllables could be learned in a single presentation or, as he put it (p. 33), a "first fleeting grasp" of the items. Studies of the childhood development of immediate memory soon followed in the form of memory span experiments (Bolton, 1892; Jacobs, 1887).

Miller, Galanter, and Pribram (1960) introduced the term working memory to describe memory for one's near and distant future plans, and Sperling (1960) greatly expanded our understanding of temporary memory in general, and specifically in the case of visual stimuli. Baddeley and Hitch (1974) popularized the term working memory and applied it to a multicomponent system with devoted automatic buffers (verbal and by implication nonverbal visual) as well as an attention-demanding central resource comprising executive processes. Tests of limited resources were later extended to infant and child development by numerous investigators, for example in tests of a relation between memory and processing speed in children (Case, Kurland, & Goldberg, 1982; Hulme, Thomson, Muir, & Lawrence, 1984). More recent and closely-germane strands of the developmental research history are well-covered in the monograph.

A complementary set of key beaver dams are the theoretical explanations of the development of working memory and cognition. As noted in the monograph, many investigators have offered verbal and pictorial explanations for how working memory operates, or how it develops. That is still a far cry from a principled, mathematical model of how working memory develops. One can imagine that certain verbal or pictorial models lead to particular predictions, but sometimes this kind of speculation depends on assumptions that have not been made clear, and sometimes are not fully appreciated even by the investigator doing the speculating.

Mathematical modeling leaves less room for unappreciated assumptions because one needs to fill in the assumptions to yield the desired mathematical result.

Work using equations to specify psychological processes seems to have begun with Ernst Weber and Gustav Fechner in the late 1800s. Estes (1950) was perhaps the first to show that mathematical precision could be brought to the task of stating models of learning and memory in a more rigorous fashion, and many related approaches have followed. Investigators sometimes called neo-Piagetian (McLaughlin, 1963; Pascual-Leone & Smith, 1969) used concepts of temporary memory and information processing to explain conceptual development in childhood, including some mathematical specification. Others have pioneered various principles that were incorporated into the present modeling, such as the principle of lateral inhibition applied to cognitive concepts in memory by Walley and Weiden (1973).

**The Present Use of Mathematical Modeling**

Before discussing the topic of mathematical modeling further, I would note that my qualifications to this topic include being all over the map in terms of my attitude. I have a love-hate relationship with modeling. I can see important pitfalls of mathematical modeling, and I can see enormous benefits. I have ignored some mathematical models that I am expected to know, and I have done mathematical modeling myself (generally with technical help). However one feels when reading or trying to read a mathematically-involved work like the present monograph, I am probably sympathetic.

To become a connoisseur of mathematical modeling, one must first appreciate that there are multiple aims of the modeling, and the correct aim must be attributed for a model to be appreciated. The present modeling shows how certain theoretical accounts of working memory development are *possible*, not necessarily how they are necessary. Is it possible to explain why

children do steadily better in working memory tasks as they get older? Why some materials are remembered better than others? Why what develops may include both the number of items in working memory (for example, how many colors) and the precision by which those items are represented (the fidelity of the remembered shades)? Can we understand why performance depends to some extent on the individual and to some extent on the task he or she is to carry out? How about dependence on the similarity of items to be remembered and the interference between them (cf., Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012)? Can all of these factors be understood with the same simple principles, tying together development from infancy through childhood? In the present work, these questions are all answered in the affirmative. A working assumption is made that, as infants and children develop, the connectivity in the neural architecture is strengthened. At least with one reasonable architecture, the simple principle of connectivity is said to account for all of these phenomena.

For the modeling results to be useful, their limits must be understood. There need be no claim that the details of the architecture are in fact correct. Perhaps a completely different model would also explain the facts equally well. What can be established, though, is that the model, though itself complex in its mathematical details, is essentially an argument for simplicity. Before, there may have been a perceived need for different principles to explain the infant and child data. Several complex mechanisms might have been thrown in to explain separately the development of capacity in terms of the number of items represented in working memory and the precision of the representations. Instead, these details can be seen as falling out of the same architecture with the principle of increasing connectivity, leading to increasing stability of the representations.

One naturally hopes that what has been proven possible in one's model eventually proves to be the actual case, or even proves to be necessary to account for the results. Then one could be considered "right." Even without being right, modeling work is useful as it sharpens up the concepts being discussed, which aids in evaluating them.

What the model does best is to strengthen the plausibility of a dynamic systems approach. As stated in the monograph, "Within dynamic systems theory, the focus is on how behavior emerges from multiple underlying causes, encouraging researchers to explore the various contributions to behavior, and to evaluate the robustness of behavior relative to the circumstances required to support them." This mundane-sounding theoretical statement actually runs counter to the thinking of Jean Piaget, who tended to believe that once a mental structure was fully acquired, it was robustly demonstrated across task demands. The neo-Piagetians would have disagreed. Once, as a teaching assistant during graduate school in the later 1970s, I confirmed to my own satisfaction the neo-Piagetian stance. By mid-childhood, children are supposed to understand that water poured from a squat beaker to a thin one does not change in volume, and that clay rolled from a ball into a sausage shape does not change in volume either. With undergraduate students, I upped the level of complexity by asking what would happen if heavy clay in a ball shape versus a sausage shape were totally submerged into identical beakers of water. Many college students incorrectly predicted that the sausage-shaped clay would raise the water level more, a failure of the conservation-of-matter principle in a complex context.

The model also shows that there is room for error in the encoding, maintenance, processing, decision, and response phases of a task. We may choose only one of these as the source of error in a particular simplified model, but no model of behavior across contexts can survive without coming to grips with processing during all of the phases of the task.

**For the Future:  Some Unanswered Questions**

The first and perhaps foremost unanswered question I have is how long the model can persist before the need to modify it sets in.  When the model does have to be modified, how extreme will the modification have to be?  How many detailed facts can the model account for and still elegantly show that the increasing-connectivity principle accounts for the development of working memory across tasks?

There is some mystery left for me with regards to the effect of the similarity of the items to be remembered.  It was stated that "When multiple peaks form near one another, their related inhibition combines, making it more difficult to form new peaks." Some of the sources cited, however, indicate that sets of more similar items, such as several shades of green, can be remembered better than sets of less similar items, such as different colors together (e.g., Lin & Luck, 2009). I cannot figure out how to reconcile the principle with the findings.

Although the developmental results that were accounted for are rich and varied, they do generally seem to involve just about every aspect of working memory performance getting better with age. That pattern of development in itself has been referred to as "the dull hypothesis" (Perfect & Maylor, 2000); the dull hypothesis can be rejected when one finds an interaction between tasks and age groups. To some extent, in the present approach, the dull hypothesis is rejected in the fitting of the model to young children in two tasks, the typical infant task and the typical child task.

In the future, however, it may be necessary to reject the dull hypothesis more severely. Among the predictions of the model is that with development, memory representations gain more stability and therefore are preserved better across a retention interval; that is, in more mature participants, the representations decay less than they do in younger ones. In general, though, we

have not found that decay difference across age groups. In one procedure (Cowan, Nugent, Elliott, & Saults, 2000), children were tested on memory for lists of digits that were ignored at the time of their presentation and then occasionally were cued for recall 1, 5, or 10 s after the last digit in the list. With the list length adjusted to each individual's span, the rates of decay of the list across 10 s did not change significantly between 7 and 20 years. There was, however, a large age effect restricted to the final serial position, which could be accounted for by age differences in either sensory memory persistence or covert attention-shifting to the end of the list. There is a similar finding of an age difference in the decay of isolated tone information (Keller & Cowan, 1994). Using spatial arrays of unfamiliar characters, followed by a mask to reduce the use of sensory memory, Cowan. Ricker, Clark, Hinrichs, and Glass (2014) found no difference between 7-year-olds and college students in the rate of decay of memory for array characters across 10 s. Taken together, these results suggest that a key principle of the model may not apply in the same way to sensory and conceptual information.

To understand age differences in the decay of information, perhaps one needs to specify the mechanism that produces stabilization. Camos and Barrouillet (2011) have studied the ability to use spare time to refresh working memory representations. They presented series of animal pictures to be remembered and, between each pair of animals, either 1 or 2 colored spots to be named. An important change occurred between 6 and 7 years of age. In 6-year-olds (kindergarteners), performance was better when the total time between animals was shorter. In 7-year-olds (first-graders), performance was better when the proportion of time between animals that was free for refreshing was high, no matter whether the total time was short or long. The results suggested that 6-year-olds do not use the refreshing process and therefore are subject to steady decay, whereas decay is counteracted by refreshing in 7-year-olds. This study differs from

the ones by Cowan et al. (2000, 2014) in that those studies presented conditions for which

refreshing would be difficult or impossible (because the items were unattended digits or attended

arrays of unfamiliar characters). In all, the results suggest that age differences in instability of

representations might often be attributed to the growing effectiveness of attention-demanding

refreshing processes.  The idea is that only in tasks in which older participants can refresh items

can they stabilize their working memory representations during the maintenance period better

than younger, less mature participants.

The notion that attention-based processes are used for refreshing does not contradict the

model presented in the present monograph, but it does appear to restrict the scope of the model.

The scope may have to be restricted to situations in which there are age differences in a process

that can be mapped onto better stability of the traces.  For some stimuli, in some age groups,

such as letters in children 5-7 years old, there will be age differences in knowledge that can result

in differences in stability of the representations that are already manifest at the time of encoding.

For other stimuli, age differences occur at the time of maintenance through refreshing.  These

sorts of differences would be expected to produce age differences in decay.  For stimuli that are

neither encoded nor refreshed advantageously by older age groups, there may be no difference in

decay.

The finding of no age difference in decay is interesting when it is obtained with the list

length adjusted to the participant's ability (e.g., Cowan, 2000) or with age groups at different

levels of performance despite no decay differences (e.g., Cowan et al., 2014).  The intriguing

thing here is that age group effects in performance level and decay are dissociated. It is unclear

to me how to modify the present dynamic systems model to produce this dissociation.  It seems

as if the "self-sustaining" state of working memory may be self-sustaining in some ways based

on automatic processes (such as encoding clarity that may often favor more mature participants who have more knowledge) and self-sustaining in other ways only when voluntary strategies can be implemented (such as memory persistence over time, which may favor more mature participants only for stimuli that lend themselves to refreshing or rehearsal processes).

Beyond empirical issues such as this, it is possible to use modeling in a more specific manner than was done in the present monograph. Many researchers attempt to produce models that match the data so closely that they can present a pattern of predicted results in one panel of a figure and a panel of obtained results next to it. In this kind of approach, to get the data and model to resemble one another so closely, there are usually a host of auxiliary assumptions resulting in parameters in the equations with arbitrary values. The strength of the approach is that there can be no doubt that one can get the actual pattern of results from the model; the down side is that one still has to figure out how much of the success comes from parameters that reflect basic principles of the model (e.g., connection strength) and how much of the success depends instead on parameters that were supposed to be incidental or unimportant but actually are doing the heavy lifting, forcing the model to match the data in a manner that has little to do with its stated principles. A related problem is that it is difficult to get these more specific models to account for a variety of circumstances as the present modeling does; for example, I have seen serial recall models that could not be modified in a foreseeable way to account for free recall.

In the more specific modeling approaches, one often compares multiple models that differ in important ways and finds out which model fits the data better according to standard fit statistics. In the present dynamic systems approach, it would be possible to present models with connectivity that develops at different rates for different layers in the model, which may make the model more complex but may be consistent with evidence that different parts of the brain

develop at different rates (Sowell et al., 2003; Thomason et al., 2008). Some fit statistics (such as AIC and BIC) are designed to penalize models for extra complexity and see if the more complex models are worth it.

Finally, modeling is a tricky exercise when one takes the popular approach of comparing two or more possible models to determine which model is more apt. In a recent effort (Cowan et al., in press), we tried out models of how adults perform in a new task in which they were presented with two arrays of colored spots in succession, and asked to judge how many of the array items changed color between a studied display and a test display. In our first modeling approach, a separate decision was assumed to be made by the participant for each array item. The model fit the pattern of means beautifully, but utterly failed to fit the distribution of responses in each condition, leading to a rejection of the model in favor of other models that would not have been considered, had the first model not failed.

To sum up, modeling is a tricky enterprise. The present work very nicely sets out a simple neural scheme and then follows the implications of that scheme for working memory development in the case of visual arrays of items to be remembered. Perhaps the strongest recommendation for the model is that it served as a motivator to get Simmering to test the same children on both the usual infant and usual child procedures, leading to an elegant set of results that in turn led to further refinement of the model. The model served as a very nice proof that one can go far with basic, elegant neural principles. In a similar manner, in the future one could imagine that the modeling would help to guide further work on the nature of decay effects, the relation between items in working memory and precision of the representations, and potential differences between the rates of development of these concepts. It might lead to predictions about when and in what way working memory can be trained. In normal individuals there has

been little evidence that working memory training helps to improve tasks other than those similar to the one trained (e.g., Melby-Lervåg & Hulme, 2013; Redick et al., 2013), but there might be more hope in individuals with processing abnormalities.  It is possible to impair a model and then see how it might be trained, leading to predictions that could be tested in real individuals,

       The work illustrates that further progress depends on close communication between researchers with empirical and modeling orientations, as well as between researchers emphasizing development in infancy versus later childhood.

**References**

Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation*, Vol. 8. New York: Academic Press. (pp. 47-89)

Bolton, T.L. (1892). The growth of memory in school children. *American Journal of Psychology, 4*, 362-380.

Camos, V., & Barrouillet, P. (2011). Developmental change in working memory strategies: from passive maintenance to active refreshing. *Developmental Psychology, 47*, 898-904.

Case, R., Kurland, D.M., & Goldberg, J. (1982). Operational efficiency and the growth of short term memory span. *Journal of Experimental Child Psychology, 33*, 386-404.

Cowan, N., Hardman, K., Saults, J.S., Blume, C.L., Clark, K.M., & Sunday, M.A. (in press). Detection of the number of changes in a display in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*.

Cowan, N., Nugent, L.D., Elliott, E.M., & Saults, J.S. (2000). Persistence of memory for ignored lists of digits: Areas of developmental constancy and change. *Journal of Experimental Child Psychology, 76*, 151-172.

Cowan, N., Ricker, T.J., Clark, K.M., Hinrichs, G.A., & Glass, B.A. (2015). Knowledge cannot explain the developmental growth of working memory capacity. *Developmental Science, 18*, 132-145.

Ebbinghaus, H. (1885 / 1913). *Memory: A contribution to experimental psychology*. Translated by H.A. Ruger & C.E. Bussenius. New York: Teachers College, Columbia University. (Originally in German, Ueber das gedächtnis: Untersuchen zur experimentellen psychologie)

Estes, W. K. (1950). Toward a statistical theory of learning. *Psychological Review, 57*, 94–107.

Hulme, C., Thomson, N., Muir, C., & Lawrence, A. (1984). Speech rate and the development of short term memory span. *Journal of Experimental Child Psychology, 38*, 241-253

Jacobs, J. (1887). Experiments on "Prehension." *Mind, 12*, 75-79.

Keller, T.A., & Cowan, N. (1994). Developmental increase in the duration of memory for tone pitch. *Developmental Psychology, 30*, 855-863.

Lin, P.-H., & Luck, S.J. (2009). The influence of similarity on visual working memory representations. *Visual Cognition, 17*, 356-372.

McLaughlin, G. H. (1963). Psycho-logic: A possible alternative to Piaget's formulation. *British Journal of Educational Psychology, 33*, 61-67.

Melby-Lervåg, M., & Hulme, C. (2013). Is working memory training effective? A meta-analytic review. *Developmental Psychology, 49*, 270–291.

Miller, G.A., Galanter, E, and Pribram, K.H. (1960). *Plans and the structure of behavior*. New York: Holt, Rinehart and Winston, Inc.

Oberauer, K., Lewandowsky, S., Farrell, S., Jarrold, C., & Greaves, M. (2012). Modeling working memory: An interference model of complex span. *Psychonomic Bulletin & Review, 19*, 779–819.

Pascual-Leone, J., & Smith, J. (1969). The encoding and decoding of symbols by children: A new experimental paradigm and a neo Piagetian model. *Journal of Experimental Child Psychology, 8*, 328-355.

Perfect, T. J., & Maylor, E. A. (2000). Rejecting the dull hypothesis: The relation between method and theory in cognitive aging research. In T. J. Perfect & E. A. Maylor (Eds.), *Models of cognitive aging* (pp. 1-18). Oxford: Oxford University Press.

Redick, T. S., Shipstead, Z., Harrison, T. L., Hicks, K. L., Fried, D. E., Hambrick, D. Z., Kane, M.J., & Engle, R. W. (2013). No evidence of intelligence improvement after working memory training: A randomized, placebo-controlled study. *Journal of Experimental Psychology: General, 142*, 359-379.

Sowell, E. R., Peterson, B. S., Thompson, P. M., Welcome, S. E., Henkenius, A. L., & Toga, A. W. (2003). Mapping cortical change across the human life span. *Nature Neuroscience, 6*, 309-315.

Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs, 74* (Whole No. 498.)

Thomason, M.E., Race, E., Burrows, B., Whitfield Gabrieli, S., Glover, G.H., & Gabrieli, J.D. (2008). Development of spatial and verbal working memory capacity in the human brain. *Journal of Cognitive Neuroscience, 21*, 316 32.

Walley, R.E., & Weiden, T.D. (1973). Lateral inhibition and cognitive masking: A neuropsychological theory of attention. *Psychological Review, 80*, 284 302.