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# Initiating the Formalization of Theories of Cognitive Aging

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Although the relevant knowledge base is still impoverished, the time may be appropriate to attempt to develop and investigate formal models of cognitive aging that incorporate explicit mechanisms to account for age differences frequently observed in measures of cognitive functioning. An initial model based on an associative network metaphor is described, in which age declines in fluid or process aspects of cognition are attributed to a reduction in either the number of simultaneously active nodes, the maximum allowable activation, or the rate of propagating activation between nodes. Results from a computer simulation are consistent at a first level of approximation with many cognitive aging phenomena, and the model is shown to provide a plausible account of age differences in an area that has previously resisted explanation. Although this particular model is only one of many that could be formulated at the present time, it is argued that more rapid progress in theoretical understanding of cognitive aging phenomena will be achieved by attempting to specify one's assumptions and hypotheses in a formal and explicit manner.

The field of cognitive aging is, currently, nearly devoid of explicit theories about the causes of age-related differences in cognitive functioning that are applicable to more than a few narrowly defined phenomena. This is a potentially serious problem because scientific progress in a given field seems to require theoretical frameworks not only to organize and integrate the relevant research literature, but also to establish priorities of importance for future research. Broad generalizations are sometimes treated as explanations, but their vagueness makes it difficult to determine exactly what they can and cannot explain. For example, because there are apparently no explicit definitions of constructs such as effort, attentional capacity, or processing resources, it is not clear whether explanations invoking these or analogous concepts are either necessary or sufficient to account for age differences in cognitive functioning. In fact, it is quite possible that interpretations relying on such nebulous constructs are only masquerading ignorance in what is actually vacuous terminology.

It is for reasons such as those stated above that a scientific theory is often considered useful or valuable in proportion to the rigor and explicitness with which it is expressed. A major goal of the present article is to encourage the initiation of efforts to develop and investigate formal or computational models that incorporate testable hypotheses about the nature of cognitive aging.

The article is organized in the following manner: First, some of the major phenomena that seem to require theoretical explanation in the area of cognitive aging are briefly summarized. Second, one particular type of formalism—spreading of activation through a parallel interactive associative network—is adopted as the medium for implementing and examining theoretical assumptions. Third, alternative sets of assumptions are discussed, and the manner in which they have been expressed in a very simple computer simulation is described. The fourth section consists of a brief report of major results from the simulation, and a discussion of possible parallels between these results and certain empirical phenomena in the area of cognitive aging. Section five of the article is a case study description of an instance in which the use of a formal model has led to insights not attained with more traditional research approaches. A brief summary of the advantages and disadvantages of formal modeling in the field of cognitive aging constitutes the sixth and final section of the article.

As previously noted, the ultimate goal of these efforts is to promote the development of formal (i.e., rigorous, precise, and at least potentially quantitative) models of cognitive aging. We are clearly very far from actual realization of such models. Although the preliminary model outlined here is also inadequate because the amount of detail is not yet sufficient to allow many specific predictions, it is hoped that the current discussion will reveal the promise in this perspective, and also will serve to indicate some of the major issues that need to be addressed before further progress in the formal modeling of cognitive aging phenomena can be expected.

## What Needs to be Explained

I once began a talk by stating that I was first going to summarize the indisputable facts of cognitive aging, and only then discuss some of the speculations concerned with the effects of age on cognition. After a brief pause, I said "So much for the facts, now for the speculations." Of course, my intent was to emphasize the tentative status of what was considered knowledge in

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cognitive aging, but even at that time I was aware that I was exaggerating the situation. There is clearly enough evidence to consider certain phenomena well established, and it is reasonable that these provide the initial foundation for theoretical systems designed to account for the effects of aging on cognitive functioning. In particular, there seems to be little argument that across the adult years there is both a decline in several aspects of cognitive functioning and, at least stability, if not actual improvement, in other aspects of cognitive functioning. Both of these aspects should thus be incorporated into a complete and viable theory of cognitive aging.

The phenomenon of age-associated cognitive decline has been reported in numerous cross-sectional studies involving a large variety of measures of memory, reasoning, and spatial abilities, and can be easily documented with several types of comparisons. For example, Salthouse (1985, Tables 11.1, 12.1, and 13.1) tabulated 54 correlations between adult age (ranging from about 20 to 70 years) and various measures of cognitive performance abstracted from many studies in the published literature. Median correlations were −.33 for the 22 correlations with measures of memory performance, −.38 for the 18 correlations with spatial ability measures, and −.35 for the 14 correlations with measures of reasoning effectiveness. The same tables also contained values of the average score of the older adults expressed in standard deviation units of the young adults, again based on data from previously published studies. The medians of these values were −1.26 for the 67 memory contrasts, −1.27 for the 22 spatial ability contrasts, and −1.60 for the 22 reasoning contrasts. Results such as these clearly indicate that increased age in adulthood is associated with fairly substantial reductions in effectiveness across a broad range of cognitive abilities. Although it may not be necessary that a theory use the same mechanism to account for the effects of aging in each aspect of cognitive functioning, a successful theory must be broad enough to encompass age-related phenomena spanning what are often considered to be quite distinct categories of cognition.

However, although age-related differences have been reported in many aspects of cognitive functioning, there are notable exceptions to this general phenomenon. In fact, most comprehensive surveys of the research literature concerned with cognitive aging have acknowledged a distinction between at least two classes of cognition—one representing something corresponding to native or basic capacity, and the other reflecting cumulative knowledge acquired from previous experience. For example, Jones and Conrad (1933) suggested that the Information and Synonym–Antonym (vocabulary) subtests in the Army Alpha measured acquired knowledge, whereas other subtests (e.g., Analogies, Number Series Completion) measured native capacity. Hebb (1942) used a slightly different distinction in his claim that intelligence consisted of two factors, one concerning the present power of reasoning, synthesis, and invention, and "the other being the lasting changes of perceptual organization and behavior induced by the first factor during the period of development" (p. 287). Cattell (1963) and later Horn (e.g., Horn, 1967, 1975, 1982; Horn & Cattell, 1966) elaborated on Hebb's ideas, referring to the former as fluid intelligence because "it can 'flow into' a wide variety of intellectual activities," and the latter as crystallized intelligence because it "is a precipitate out of experience" (Horn, 1967).

The authors cited are just a few of the many who have either proposed or accepted a distinction between at least two classes of cognitive abilities in adulthood. In fact, the following quotations suggest that the multifaceted nature of cognitive aging was apparently evident to acute observers from the time of the early Greeks:

> Solon was under a delusion when he said that a man when he grows old may learn many things—for he can no more learn much than run much; youth is the time for any extraordinary toil. (Plato, *Dialogs*, Phaedrus, Section 536-D)

> It is in old men that reason and judgment are found, and had it not been for old men no state would have existed at all. (Cicero, *De Senectute*, chap. xix, Section 67)

A multidirectional conceptualization of cognitive aging has thus been prevalent in informed discussions across a span of literally thousands of years. There is also considerable empirical evidence that different ability measures often exhibit quite different age trends (e.g., Horn, 1967, 1975, 1982, Horn & Cattell, 1966). It is therefore incumbent on any serious theory formulated to account for cognitive aging phenomena to incorporate some type of distinction between processes that appear to decline in efficiency across adulthood, and the products of prior processing that may continuously accumulate.[1]

However, it is not sufficient merely to acknowledge a process-versus-product or fluid-versus-crystallized dichotomy in a descriptive sense without an attempt to explain the mechanisms responsible for either type of phenomenon. That is, one still needs an explanation for why effectiveness in many process aspects of cognitive functioning declines across the range from about 20 to 70 years of age, and why there are few declines, and often improvements, in measures thought to reflect previously acquired knowledge or products.

The minimum requirements for a successful cognitive aging theory, therefore, seem to be acknowledgement of different age trends for process and product aspects of cognitive functioning, and specification of the mechanisms responsible for these distinct patterns. There are, of course, many other cognitive aging phenomena in need of explanation, but the process–product distinction appears so fundamental in cognitive aging that only if a theoretical system were able to provide plausible accounts of these phenomena would it warrant closer examination.

## Selection of a Fertile Metaphor

Frequently, the first step in developing a scientific explanation is to identify a metaphorical system in which potential explanatory mechanisms can be conceptualized. Two such systems are currently in vogue in the field of cognitive psychology—pro-

[1] Although the distinction between product and process is conceptually unambiguous, it is important to emphasize that it may be quite difficult to find a task that yields a pure measure of either process or product. Processes of cognition are probably emphasized more by tasks in which simple and familiar material has to be transformed or manipulated in some manner, and one's store of cognitive products (which includes procedural as well as declarative information) is probably reflected by performance in tasks dependent on previously acquired knowledge, but nearly all tasks are likely to involve a mixture of product and process.

duction systems and spreading-activation networks. Although a network metaphor has been adopted for the current discussion, it is important to point out that a production system metaphor might also have been used to illustrate the usefulness of formal modeling in the area of cognitive aging. For example, in production systems, information processing is postulated to occur by means of a sequence of productions, each consisting of a calling condition and an associated action or response. The process–product distinction previously referred to might therefore be incorporated into a production system by hypothesizing that there is an age-related decline in the ease of forming or accessing productions, but that the additional experience often associated with aging either increases the complexity or number of productions, or adds to the strength of existing productions.

Information processing within the network metaphor is considered analogous to the spreading of activation or excitation through an associative network. The structure of the network consists of many nodes (roughly equivalent to concepts) with numerous interconnecting linkages (roughly equivalent to associations), and it is often conceptualized in terms of a hierarchy with sensory levels at the bottom and progressively more abstract forms of processing at successively higher levels. Network models are loosely related to brain processes and neural nets, but they are at a somewhat higher level of abstraction, and it is important to realize that the scale of even the most elaborate models fails to approach the complexity of the human brain. To illustrate, the networks considered later in this article have either 30 or 40 nodes with 0 to 6 connections per node, whereas the human brain has been estimated to have approximately $10^{10}$ neurons with between $10^3$ to $10^4$ connections to each neuron. It is therefore unrealistic to expect network models to represent all of cognition; instead, they should be viewed primarily as a tool to help understand how certain aspects of cognitive functioning might be derived from the interaction of relatively simple computational units.

A key factor in many network models is that processing is postulated to be parallel within and between levels, and interactive in nature such that processing flows in a top-down, as well as bottom-up, manner. Because processing is occurring simultaneously in many different nodes, parallel models are in distinct contrast to models postulating discrete sequential processing. Some suppression of the activity in competing nodes is possible if mutual inhibition is allowed, but consideration of the concurrent activity in numerous quasi-independent units leads one to appreciate why Selfridge (1966) used the term *pandemonium* as the name for one of the earliest models relying on parallel processing.

Although the notion of interactive processing has only recently been incorporated into information-processing models of cognition, the basic idea has been around for some time. For example, one of the clearest descriptions of the mixture of bottom-up and top-down processing, and one that also captures the essence of the present position, was provided by Spearman in 1923:

> the eductive growth is unlike the building of a wall, where first one layer is finished, and then another above it, and so on. It is more like the waxing of a tree, which does not first complete its roots, then stem, then branches, then leaves, all in succession, but develops all these overlappingly. So in the cognitive cellulation also, the lower levels are allowed only a limited degree of priority. While they are still extremely obscure, the upper levels already begin growing also, and to the full extent that their as yet imperfect understructure becomes from moment to moment capable of supporting. (p. 82)

Interactive parallel models have been found to provide reasonably comprehensive accounts of phenomena in word perception (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982), transcription typing (Rumelhart & Norman, 1982), learning and memory (McClelland & Rumelhart, 1985), and topics such as visual perception, schema acquisition and utilization, speech perception, and language acquisition (e.g., Dell, 1985; Feldman & Ballard, 1982; Sabbah, 1985; Waltz & Pollack, 1985; also see chapters in Hinton & Anderson, 1981; McClelland & Rumelhart, 1986; and Rumelhart & McClelland, 1986). Because models of this type appear to have several advantages over more familiar serial models of information processing, it is useful to examine contributions they might make to understanding the effects associated with aging on cognitive functioning.

Most of the discussion that follows will be rather abstract, with only loose references to specific task processes. Although much more explicit information would obviously be necessary for models of this type to be considered explanatory in any particular domain, it is nevertheless desirable to examine the basic operation of network models as they might be adapted to account for phenomena of cognitive aging. Of particular interest are alternative ways within the network framework of conceptualizing aging to incorporate both the stable or incremental (cognitive product) aspects, as well as the decremental (cognitive process) aspects.

## Network Representations of Product and Process

Knowledge, or the quantity and quality of intellectual products to which one has access, is represented in network models in terms of the number of nodes, and the pattern and complexity of their interconnections. One of the easiest ways to portray alternative conceptualizations of the effects of varying degrees of knowledge in a network is, therefore, by illustrating how a network structure might be altered with different amounts of knowledge. Figure 1 contains such an illustration with A indicating the base or minimal-knowledge network, and B, C, and D indicating various ways in which a network might be embellished or enriched to reflect increased knowledge.

Notice that relative to the network in Figure 1A, the other networks have either (a) a greater number of nodes with the same number of connections, Figure 1B; (b) a greater number of connections among the same number of nodes, Figure 1C; or (c) the same number of nodes and connections but with the connections differing in a property such as the strength of the propagated activation, Figure 1D.

Figure 1B might be a plausible representation of increased knowledge because it contains more nodes,[2] which can be con-

[2] It is important to point out that postulating additional nodes in a network does not mean that new neurons must be formed in the nervous system. All that is required is that new meaning be attached to previously undifferentiated nodes in the form of active connections with nodes whose meaning has already been established.

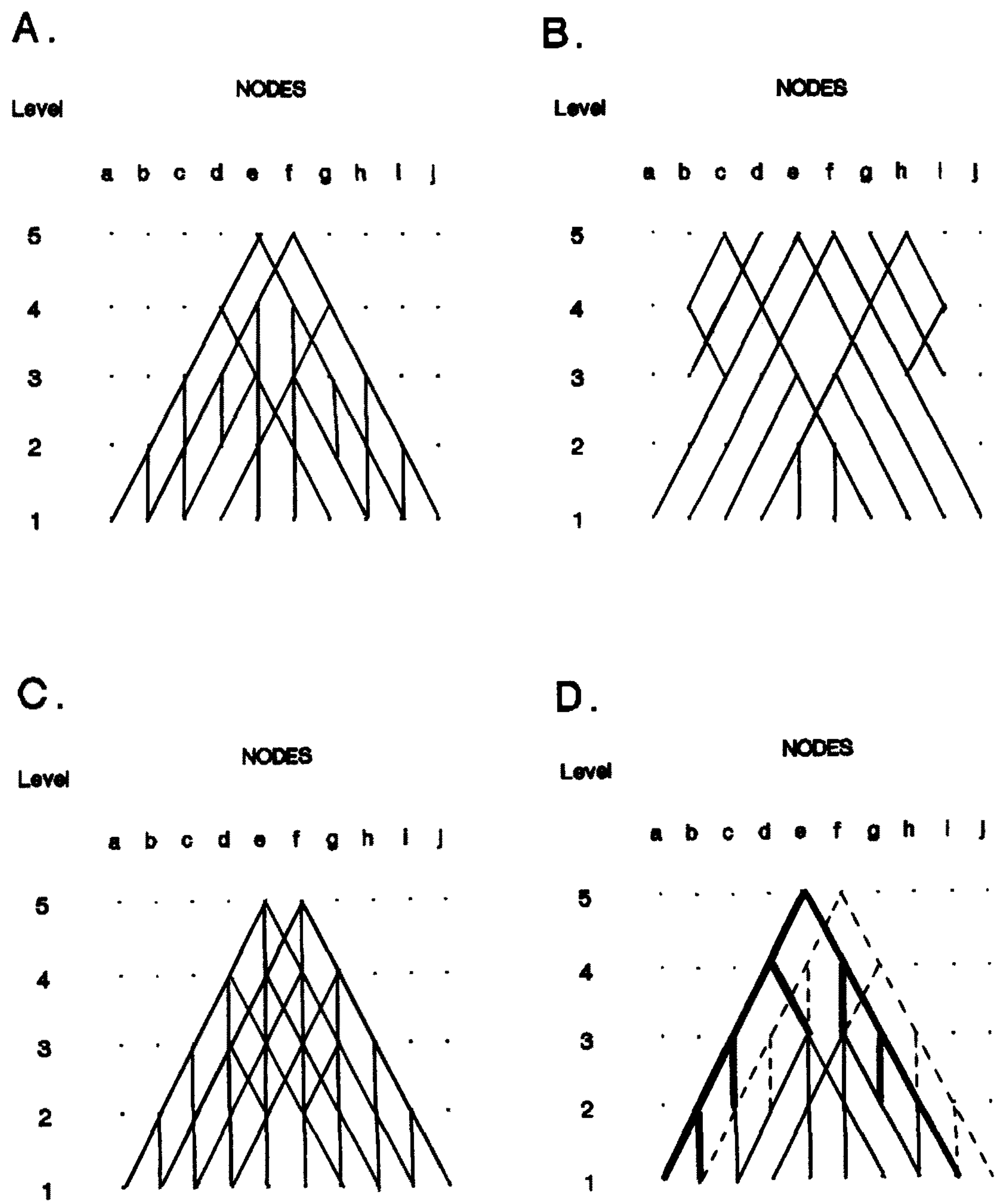


*Figure 1.* Illustration of a hypothetical network structure (A), and how knowledge might be represented by additional nodes (B), additional connections (C), and differential connection strength (D).

sidered analogous to facts or concepts, than the network represented in Figure 1A. Because in network models a node has meaning only with respect to the connections it has with other nodes, it may actually be unrealistic to suggest that a network with more nodes but containing the same total number of connections represents greater knowledge than does another network. Nevertheless, this alternative is at least conceptually feasible, and thus it serves to illustrate the richness of the theoretical distinctions possible within network representations.

An alternative way of thinking of knowledge is not simply in terms of a greater number of facts, but with respect to a denser and more richly interconnected set of relations among the same core set of facts. Figure 1C is therefore another plausible way of representing increased knowledge because it has a greater number of interconnections among the same number of nodes than the base network in Figure 1A.

Still another means of conceptualizing variations in knowledge is that people of different levels of knowledge are distinguished primarily in terms of the organization of the information they possess. A network with greater knowledge, therefore, might not be one in which all connections are equally weighted, but one in which the more salient or more probable associations have stronger connections than the weaker or less frequent associations. The contrast between Figure 1D and Figure 1A embodies this conceptualization of knowledge.

Just as there are several ways of conceptualizing the embodiment of product knowledge in associative networks, so also are there numerous ways of conceptualizing the source of limitations on the efficiency of processing within a network. For example, one means by which process efficiency could be impaired is through a decrease in the number of nodes that can be simultaneously active, in a manner roughly analogous to a reduction of working-memory capacity. That is, if only a portion of the 30 nodes in the network of Figure 1A could be simultaneously active, certain types of processing would either be delayed, or may not even be able to be carried out at all.

Another potential source of process inefficiencies in an associative network is in terms of a limitation on the total amount of activation possible within the network at any given time. The psychological analog of this might be considered a reduction in the attentional capacity or energy that is often postulated to be necessary for the effective execution of many cognitive processes. Because activation is the processing fuel of associative networks, any limits on the total amount of activation simultaneously available within a network could be expected to impose severe and widespread constraints on many aspects of processing.

Still a third possibility for conceptualizing process limitations in network models is in terms of alterations in the rate of propagating activation from one node to another. That is, if there is an increase in the time required to transmit information along the associative networks, then the simultaneity of activation essential for certain types of interactive or contingent processing will be severely disrupted. This interpretation is obviously very similar to psychological views that the speed of processing information is an important determinant of cognitive effectiveness.

Although the preceding examples suggest that the network metaphor is a potentially fertile source of hypotheses in the field of cognitive aging, it may be too early to expect much success in distinguishing among these alternatives. One reason why it may be premature at this time to pursue what appears to be a natural direction for future research is that although the alternatives previously discussed appear to be conceptually distinct, they are not necessarily mutually exclusive. That is, greater knowledge may be manifested in terms of increases in both the number of nodes *and* the number of interconnections, or in terms of a greater number of interconnections *and* alterations in the strengths of those interconnections. The various types of process inefficiencies may also be interchangeable, and consequently indistinguishable, at certain levels of analysis. For example, each of the alternatives discussed could result in a reduction in the quantity of available activation. That is, activation quantity is reduced when it is directly limited, and it is indirectly reduced (a) by restricting the number of nodes if the activation from nodes in excess of the allowable number is not redistributed to the active nodes and (b) by delaying propagation if activation continues to decay during the interval between each successive propagation.

A second reason why it may be too early to attempt to distinguish among the alternative representations for either the product or process aspect of cognition is that necessary information about the degrees of product enrichment or processing impairment, or the level of implementation of either the product or process assumptions, is almost completely absent. That is, it is very difficult to contrast different conceptualizations of process inefficiencies without some means of establishing a correspondence between the degree of impairment due to, for example, limitations on the number of active nodes and limitations on the total amount of simultaneous activation. With respect to the issue of implementation, the representation could be global and apply throughout the entire network, or it could be local to specific regions of the network and apply only to certain types of processing. The further complication of determining when and where sets of assumptions hold, rather than merely if they hold, clearly adds to the difficulty of attempting to distinguish among alternative types of structural alterations or alternative types of efficiency limitations.

The preceding discussion indicates that although they may not yet be distinguishable, there are several ways of incorporating the product–process distinction in network models. Age-related stability or increments in measures of acquired knowledge would be expected as long as aging is associated with greater amounts of experience that result in an ever-increasing accumulation of structural alterations representing acquired products. And decreases in the efficiency of cognitive processing would be expected to the extent that increased age is associated with a reduction in either the maximum number of simultaneously active nodes, the maximum amount of concurrent activation, or the speed of propagating activation from one node to another.

It is interesting to contrast the present network metaphor with previous attempts to elucidate the mechanisms involved in the product–process distinction. For example, Hebb (1949) proposed that productlike increments were due to an accumulation of cell assemblies and phase sequences, whereas the efficiency of establishing or creating these structural entities decreased because of an age-related reduction in relevant brain tissue. Horn (1975) also speculated that Gc (roughly analogous to acquired products) was based on discrete neural activity along pathways built up through previous learning, and that Gf (roughly analogous to current processing efficiency) reflected readiness for new diffuse neural activity.

Implicit in each of these perspectives is a view that age-related stability or improvement in cognitive functioning is less in need of explanation within a developmental framework than is age-related cognitive decline. Whether because previous learning is less affected by physiological impairments than by new learning, or because age-associated experience has resulted in varying levels of expertise superimposed on any decline that may occur, stability or improvement in cognition across the adult years has received less attention than has age-related cognitive decline. Although one could justifiably claim that the emphasis on phenomena exhibiting age-related decline results in a distorted picture of the true capacities of older adults, it is easy to understand that given theoretical perspectives such as these, aspects of cognition that decline with increased age are given a higher priority for explanation that are those aspects that remain stable or increase.

The various perspectives do differ, however, in the specificity with which the mechanisms proposed to account for the age-related cognitive decline are described. As noted earlier, Hebb (1949) attributed age-related cognitive decline to loss in unspecified brain tissue presumed to be necessary in the establishment of neural connections, and Horn (1975) speculated that a decline in a vaguely described "readiness for neural activity" was responsible for decreases with age in cognitive functioning. One of the distinct advantages of formal models, and of the network perspective in particular, is that the cognitive declines are not attributed to poorly specified impairments that allow little or no possibility of investigation. Instead, the explicitness of the speculations in the network perspective allows them to be investigated by actually examining the processing consequences of each type of limitation in a formal system. The next section illustrates this property by describing how a very simple computer simulation can be used to analyze the consequences of imposing limitations on processing efficiency in an interactive network.

## Simulation of Network Processing

Processing in the network illustrated in Figure 1A has been simulated in a computer program loosely based on the models described by McClelland and Rumelhart (1981, 1985), and Rumelhart and McClelland (1982). The simulation is designed to examine the consequences over time of the integration of activation in an interactive hierarchical network, that is, one in which processing flows top-down as well as bottom-up. First, the general model will be briefly outlined, and then relevant aspects of its operation described in more detail.

Presentation of an external stimulus is assumed to stimulate certain Level 1 detectors, and this excitation or activation is then communicated successively to nodes at progressively more abstract (i.e., higher in the hierarchy) levels in the network. However, because activation is assumed to decay over time, the activation from connected units or nodes must converge on the target node within a limited time interval or it will fail to summate with the prior activation. If earlier activation has dissipated by the time later activation arrives, the amounts will not accumulate, and consequently the node will fail to propagate activation to other nodes.

Nodes in the model are distributed across five levels representing progressively more abstract forms of processing. Connections between nodes are stored as entries in an array, and each node's activation magnitude is indexed by the value of the variable representing that node. Although the model is intended to represent continuous processing, time is implemented in terms of discrete cycles for ease of computation.

Processing in the network is initiated by stimulating specified Level 1 nodes for a fixed number of time cycles. (For simplicity, the same stimulation magnitude has been used for all stimulated nodes.) Figure 1A illustrates that there is not a one-to-one correspondence between the lowest level nodes and nodes at the highest level, but the relative activation strength of each higher level node will nevertheless be determined by which particular lower level nodes received stimulation. For example, Node 4-d in Figure 1A will receive the strongest relative activation when only Nodes 1-a through 1-g are stimulated, whereas Node 4-g will have the highest relative activation when only Nodes 1-d through 1-j are stimulated.

Activation from the lowest level to the next lowest level in this particular network only flows upward, whereas that between other levels goes both bottom-up and top-down, but in all other respects the same dynamics govern processing for every node. The first event during a time cycle is to decay the current activation level at each node by 10% toward a baseline of zero. (This decay parameter is arbitrary, but results in more tractable patterns of temporal decay compared with much smaller or greater values.) The second processing event occurs at intervals determined by the designated processing rate. This event consists of dividing the activation at each node in half, with 50% remaining at that node and 50% distributed equally to all connecting nodes.

The last event during a time cycle is to compute the number of active nodes and the total amount of activation throughout the network, and when appropriate, to invoke restrictions on those quantities. Restriction of total activation was imposed by reducing all activation strengths proportionally, and the limitation on the number of active nodes was implemented by rank-ordering the activation strengths of all active nodes, and then reducing the strengths of the weakest ones in excess of the allowable number to zero.

Output of the simulation consists of the magnitude of activation at each time cycle for every node in the network. It is assumed that decisions are based on some property of the activation (e.g., latency, absolute magnitude, product of duration and magnitude) at the relevant nodes in the network. For simplicity it is often convenient only to report values of peak activation strength at selected nodes,[3] but most measures are highly intercorrelated and thus similar patterns would be evident with many dependent variables.

It is important to point out that the current simulation model is greatly simplified and would have to be considerably elaborated to represent any specific phenomenon. One simplification is that the model contains no provision for inhibition, and instead all communication between nodes is excitatory or additive. Although inhibition is a very powerful concept, and is probably indispensable for the construction of specific circuits to perform complex processing, it didn't seem necessary for the purposes of illustrating the application of these ideas to phenomena of cognitive aging.

The model as it currently stands is also completely deterministic in that the same output is always produced from the same input. This again is a simplifying feature, but it could easily be changed by, for example, relying on a probability distribution for the assignment of stimulation magnitudes to specific element nodes. That is, the particular elements receiving stimulation and the magnitude of that stimulation could both be proba-

[3] To avoid undesirable complexity, the discussion will refer to processing in single nodes, but this should not be interpreted as endorsing a local-representation (one concept = one node) model. An alternative, and in many respects more plausible, possibility is the notion of distributed representations in which a concept is represented by the pattern of activation occurring over sets of interconnected units.

bilistically determined, and thus any desired degree of variability could easily be introduced into the system.

Another simplifying feature of the current model is that strictly linear and continuous activation functions are used to determine node strength, rather than having arbitrary constraints imposed on the minimum (threshold) or maximum (ceiling) allowable values. Updating the activation of all nodes in the network simultaneously rather than asynchronously, was also a simplifying feature because, although simultaneous updating of activation introduces undesirable oscillations, it is considerably easier to implement than asynchronous activation.

Perhaps the most important simplification in the current model is that the network portrayed in Figure 1A is almost completely arbitrary and static. That is, the network is intended primarily for illustrative purposes and is not designed to produce any particular type of output, given certain input, nor to modify its structure to adapt to specific experiences. The resulting system is therefore much more abstract than networks constructed to represent specific types of processing by having the pattern of excitatory and inhibitory connections among the nodes arranged to produce a particular type of processing. Although this abstractness means that the current model cannot produce a detailed account of any specific task, it is a desirable characteristic when one attempts to examine the general consequences of limitations on system-status parameters such as number of active nodes, amount of activation, or rate of propagating activation. Note also that in the present context, the goal is not cognitive modeling per se, but rather modeling of the mechanisms responsible for the decrements (or increments) observed in cognitive functioning across the adult years. To the extent that those decrements (or increments) are fairly general and evident across a variety of cognitive tasks, as the data summarized earlier seem to suggest, then one need not be too concerned with the mapping of the model to specific tasks at the present time.

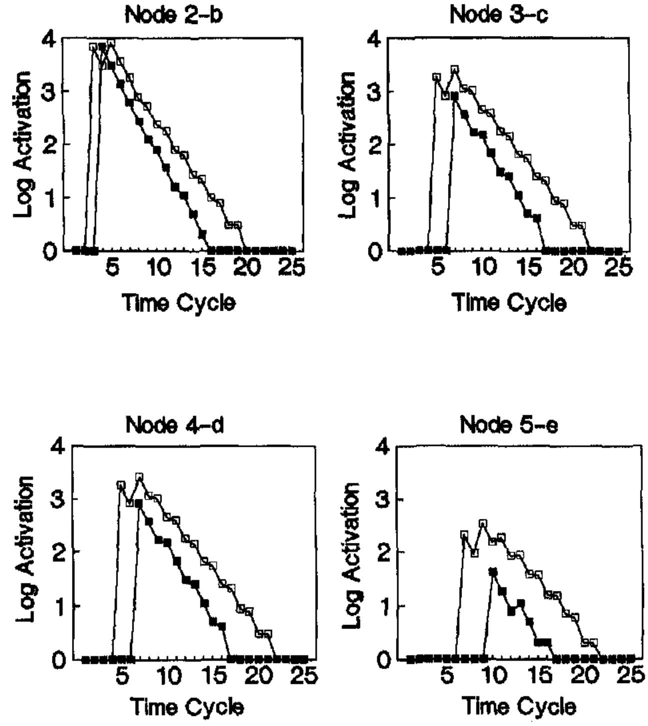


*Figure 2.* Log activation strength as a function of the time cycle from the initiation of stimulation for two rates of activation propagation for four nodes in the network. (Functions with open squares represent a fast processing rate—propagation every 2nd time cycle—and functions with solid symbols represent a slow processing rate—propagation every 3rd time cycle.)

## Results of the Simulation

As a means of summarizing the processing dynamics within an interactive network, Figure 2 displays graphs of the activation functions from nodes at four different levels in the network portrayed in Figure 1A. That is, the graphs illustrate the changes across time in the strength of activation at particular nodes in the network. Only the results of varying the rate of propagation are illustrated because of the aforementioned difficulty of establishing comparable levels of each processing efficiency limitation. At least when viewed from a broad qualitative perspective, however, the consequences of restricting the quantity of simultaneous activation and the number of active nodes appeared similar to those of increasing the interval between successive propagations.

Three points should be noted concerning the functions illustrated in Figure 2. The first is that limiting a system-status variable such as the rate of propagating activation results in gradual impairments (or what Rumelhart & McClelland, 1986, p. 134, have termed *graceful degradation*), rather than in catastrophic losses as might be predicted if a single discrete component were damaged. That is, no particular kind of processing is completely destroyed while other types of processing are preserved, but instead there appears to be a general reduction in the efficiency of most aspects of processing.

Because these efficiency differences appear despite an identical, intact network structure, many phenomena dependent on structural properties should still be evident in adults of different ages. That is, if the primary effect of aging is a limitation such as fewer active nodes, lesser amounts of activation, or delayed rates of propagating activation, then adults of all ages should be sensitive to phenomena related to structural characteristics of the network. Of course, if the effects of the structural factors are relatively weak, then some of the phenomena may be difficult to detect at reduced levels of processing efficiency. The general expectation from this perspective, however, is that aging results in a progressive impairment in the quality of information relevant to nearly all processing, and not (at least directly) in an altered system or style of processing.

Several lines of research in cognitive aging appear consistent with this expectation. For example, young and old adults have been shown to exhibit qualitatively similar priming effects in word recognition (e.g., Bowles & Poon, 1985; Burke, White, & Diaz, 1987; Burke & Yee, 1984; Cerella & Fozard, 1984; Chiarello, Church, & Hoyer, 1985; Howard, 1983; Howard, Lasaga, & McAndrews, 1980; Howard, McAndrews, & Lasaga, 1981; Howard, Shaw, & Heisey, 1986; Madden, 1986), to have similar patterns of word associations (e.g., Burke & Peters, 1986; Howard, 1980; Lovelace & Cooley, 1982; Scialfa & Margolis, 1986), to exhibit release from proactive inhibition under the same types of shifts in to-be-remembered items (e.g., Elias & Hirasuna, 1976; Mistler-Lachman, 1977; Puglisi, 1980), and to be similar in their sensitivity to, or use of, scripts (Light & Anderson, 1983) and schemata or prototypes (e.g., Hess & Slaughter, 1986). There is also considerable evidence that young and older adults are similarly affected by manipulations that can be presumed to reflect structural properties such as category typicality (e.g., Byrd, 1984; Eysenck, 1975; Mueller, Kausler, Faherty, & Olivieri, 1980), word frequency (e.g., Bowles & Poon, 1981; Poon & Fozard, 1980; Thomas, Fozard, & Waugh, 1977), and acoustic versus semantic relatedness of task material (e.g., Mueller, Kausler, & Faherty, 1980; Petros, Zehr, & Chabot, 1983). An implication from results such as these is that aging does not fundamentally alter the nature of one's cognitive structure, but that it merely reduces the efficiency of processing within that structure.

A second point to be noted about the results in Figure 2, however, is that it is inappropriate to characterize the impairments as merely quantitative rather than qualitative. That is, although the system is always operating according to similar principles, processing dependent on sufficient magnitudes of activation at higher level nodes may not be as successful, or may not even be possible, under conditions of reduced processing efficiency. For example, if a particular information-processing operation required considerable activation of Node 5-e for its successful execution, then that operation or component would be especially impaired with slow rates of propagating activation (or other forms of efficiency limitation). Depending on the context, this might be interpreted as a deficit in a specific component such as retrieval, abstraction, integration, and so forth, when in fact it could simply be a reflection of a basic limitation in processing efficiency. It is also quite possible that the reduced efficiency leads to the adoption of a different processing strategy, which, were all things equal, might be considered less effective, but which has the advantage of minimizing dependence on nodes with unreliable levels of activation.

The preceding considerations thus indicate that what might appear to be qualitative differences in the mode of processing may actually be consequences of quantitative variations in processing efficiency. Of course, one cannot automatically assume that all observed qualitative differences are attributable to reductions in processing efficiency. However, it should be recognized that purportedly qualitative differences such as the use of alternative processing strategies are themselves causally determined, and that if factors such as reduced processing efficiency are not postulated as the causes, then some other mechanisms must be proposed to account for why these strategic differences occur.

A third important point to be noted with respect to the graphs in Figure 2 is that the consequences of imposing a limitation on a fundamental processing parameter such as rate of propagating activation become more pronounced as the amount of required processing increases. That is, the difference in both the latency and the amplitude of the activation functions associated with fast and slow propagation rates increases with increases in the level at which activation strength is monitored. This characteristic of processing in network models also has its counterpart in the empirical literature. In fact, the tendency for the performance differences between young and old adults to increase as the presumed complexity of the task increases is so well established in the area of cognitive aging that it has been termed *the complexity effect phenomenon* (see Salthouse, 1985, pp. 183–189, for a review of this topic). The finding that age differences increase with task complexity is clearly consistent with the proposal that aging alters general processing efficiency because performance differences would naturally be expected to increase as the amount of processing contributing to that performance increases.

There are some apparent exceptions to the complexity effect phenomenon, however, and thus it is useful to consider if and how such exceptions might be accomodated within network models. One property of network models that has not yet been discussed is that they can easily be made dynamic in that the structure can be changed with experience. It is therefore quite possible that effects evident at one stage of practice may not be exhibited at later stages of practice because the network has altered its organizational structure as a consequence of experience. In particular, the complexity effect phenomenon may be attenuated with experience on a task because the experience resulted in the formation of more direct connections among relevant nodes in the network, thereby minimizing consequences of differences in processing efficiency. The findings by Salthouse and Somberg (1982) that age differences in the slope of memory-scanning functions were reduced with extensive practice, and by Madden (1982) that young and old adults had nearly identical scanning slopes when targets and foils were distinguished on the basis of belonging to highly overlearned sets (e.g., letters vs. digits), may be attributable to this type of mechanism.

A second characteristic of network models that might account for some apparent exceptions to the complexity effect phenomenon is a distinction between complexity and difficulty. This distinction can be important because although both complexity and difficulty can affect the level of performance on a task, they may do so by means of different mechanisms. That is, difficulty may be hypothesized to affect performance by influencing the discriminability of relevant nodes in a manner analogous to an altered signal-to-noise ratio, whereas complexity is postulated to impact on performance by altering the level or amount of processing required for a given activity. For example, the four panels of Figure 2 illustrate the effects of variations in complexity because each represents processing at a different level in the network. In contrast, Figure 3 illustrates the consequences of variations in difficulty by displaying the activation functions for three Level 3 nodes with different proportions of lower level nodes in common.

The two panels in Figure 3 portray results with two different rates of propagation, but in each case stimulation was selectively directed at only Nodes a through e in Level 1. Notice that Nodes 3-c and 3-e, which have many common connecting nodes (see Figure 1A), have activation functions that are much more similar to each other than either is to those for Node 3-g, which has few connecting nodes in common with Nodes 3-c and 3-e. These patterns suggest that it should be much easier (i.e., decisions should be faster and more accurate) to make discriminations on the basis of Nodes 3-c or 3-e versus 3-g than on

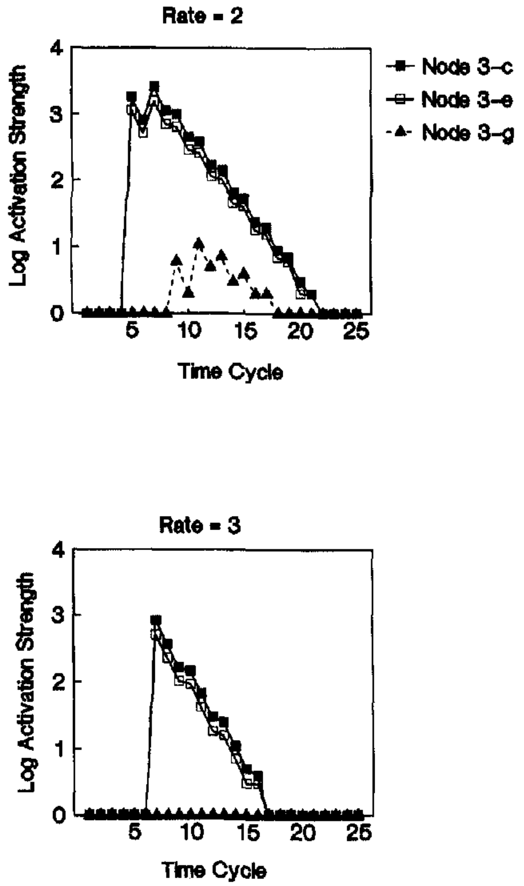


*Figure 3.* Log activation strength as a function of the time cycle from the initation of stimulation for two rates of activation propagation at three nodes with different proportions of common connections. (Rate 2 refers to propagation every 2nd time cycle, and Rate 3 refers to propagation every 3rd time cycle.)

the basis of Nodes 3-c versus 3-e. However, because there is nearly comparable distinctiveness of the functions in the two panels representing different rates of propagation, difficult discriminations (e.g., Node 3-c vs. Node 3-e) and easy discriminations (e.g., Node 3-c vs. Node 3-g) should exhibit similar performance relations across variations in processing efficiency. Another example in which different levels of processing efficiency result in parallel performance differences is discussed later in the context of research on the phenomenon of age differences in perceptual closure.

The preceding discussion, particularly that concerning the complexity effect phenomenon, indicates that the degree of impairment resulting from limitations on a general system-status parameter like rate of propagating activation is not necessarily constant in magnitude, nor restricted to only certain (e.g., speed-related) characteristics of performance. The activation functions in Figure 2 illustrate that both activation strength and the latency of activation are affected by variations in propagation rate, and that the effects tend to be more pronounced the greater the amount of required processing. Taken as a whole, these results suggest that reductions in the efficiency of processing in a parallel interactive network are compatible—to at least a first degree of approximation—with many of the phenomena of cognitive aging.

## A Common Theme of Representational Deficits?

One way of conceptualizing the cognitive consequences of less efficient processing in interactive networks is in terms of a relative impairment in the formation and use of internal representations. That is, restrictions in general processing parameters result in less activation reaching the more abstract or higher level nodes in the network, with those nodes consequently being unable to establish and maintain stable linkages with other nodes. Because an internal representation can be considered analogous to the activation of selected nodes in the network, this relative deficit at achieving stable (i.e., sufficient persisting activation) and accurate (i.e., appropriately linked to other relevant nodes) higher level activations may be characterized as a weakness in the creation and maintenance of appropriate internal representations.

A few examples (relying on the network structure portrayed in Figure 1A) will illustrate the generality of this interpretation. First, consider a memory task in which an item corresponding to Node 3-c has to be remembered. At the initial presentation this node will be activated strongly, even at relatively slow rates of propagation (cf. Figure 2). When the stimulus is removed, however, it will be represented only in terms of the residual pattern of activation within the network. Because a greater number of related nodes (e.g., 5-e) will receive substantial activation under the faster rates of propagation, the internal representation will be richer, with more potential encoding dimensions or access routes for retrieval, than the representation in the system with the slower speed of propagating activation. The more elaborate or deeper processing associated with systems having minimal restrictions on general processing parameters should therefore lead to substantial benefits in many aspects of memory performance (cf. arguments concerning depth-of-processing effects in memory).

A second example concerns the requirement of integrating separate pieces of information into a coherent representation as might be needed in spatial synthesis or closure tasks, and in assorted reasoning tasks. To illustrate, assume that Node 4-d in Figure 1-A must be activated to link Nodes 2-b and 2-f, and that this constellation is united with Node 3-g only through the activation of Node 5-e. The activation functions illustrated in Figure 2 clearly suggest that this pattern of activation is much more likely to be successful in systems with a fast than with a slow rate of activation propagation. In this respect, diminished activation in the network might be interpreted as restricting an individual's span of apprehension and as limiting the number of things that can be kept in mind at one time (cf. Horn, 1970).

The arguments I have outlined imply, therefore, that the weaker representations resulting from reduced processing efficiency could lead to performance impairments in a variety of spatial ability and reasoning tasks. Indeed, evidence linking representational weaknesses of this type to age differences has recently been reported in studies of series completion (Salthouse & Prill, 1987) and geometric analogy (Salthouse, 1987b) reasoning tasks, and mental synthesis (Salthouse, 1987a) and block design (Salthouse, 1987c) spatial ability tasks.

It is important to emphasize that characterizing the consequences of processing inefficiencies in an interactive network as representational deficits is quite different from claiming that there is an impairment in a discrete processing stage or component concerned with forming internal representations. In the latter case, one would be asserting that only a single (albeit potentially very important) phase of processing was impaired, and that other aspects of processing may be largely unaffected. The inference from the present perspective is that the constraints imposed on processing by limitations in certain basic parameters result in lower levels of activation of units, which when active, can be considered analogous to an internal representation. Therefore, although similar terminology might be used to characterize cognitive impairments under both discrete stage models and interactive network models, the mechanisms contributing to those impairments are substantially different.

Sequential stage models will undoubtedly continue to coexist with parallel interactive models, although probably at somewhat different levels of analysis.[4] For example, Rumelhart and McClelland (1986) have proposed that each symbolic operation or mental state in sequential modes of processing may correspond to a single settling of the activation in an interactive parallel network. However, certain phenomena are often better understood when examined at a particular level of analysis. Furthermore, because alterations at the level of parallel networks might account for variations in speed or accuracy at the level of symbolic operations, whereas the reverse does not seem to be the case, the more reductionistic perspective often has distinct advantages.

Interpreting cognitive aging phenomena in terms of the framework of parallel interactive processing within associative networks implies somewhat different positions on a variety of research issues than those currently dominant in the field. For example, the viewpoint that cognitive age differences originate because of limitations in general processing efficiency suggests that it may not be useful to search for a critical process or component that is uniquely impaired with increased age, or to attempt to associate age differences in performance with differences in processing strategies unless an explanation is available for why and how these strategy differences evolved. Instead, this perspective implies that researchers should seek to determine the explanatory limits of a reduction in general processing efficiency, and that they should search for neurophysiological mechanisms that might be responsible for such an efficiency reduction. An alternative to the "localizing the loss" approach characteristic of discrete symbolic models might therefore consist of constructing models to account for the performance of one group of individuals (e.g., young adults), and then determining whether an alteration in a single parameter related to general processing efficiency is sufficient to account for the performance of a second group of individuals (e.g., older adults).

Another implication of the reduced processing efficiency perspective is that it is important not to adopt too narrow a focus in attempting to account for cognitive aging phenomena because a reduction in processing efficiency is likely to have slightly different consequences in different tasks, and misleading inferences might result if one concentrated only on the manifestations evident in a single task. On the other hand, multivariate analyses should also be cautiously interpreted because variables in parallel network models may be related to one another in quite complex ways, with the value of a particular variable dependent not only on the overall degree of processing efficiency, but also on the nature of the relevant portion of the network structure and the level of processing associated with that variable. In other words, merely because variables share a common cause does not necessarily mean that the variables will exhibit equivalent consequences of that cause.

And finally, the network perspective suggests that processing efficiency can only be accurately compared if the network structure is very similar, if not actually identical. To the extent that experience alters the network structure, therefore, a researcher interested in investigating possible differences in processing efficiency must have some means of controlling the quality and quantity of relevant experience. This may well result in the study of simple and artificial tasks that have little or no ecological validity, but that may neither be necessary nor desirable if one believes that performance is influenced by processes related to both age and experience, and the immediate goal is to investigate only the former.

## A Case Study

The study of age differences in perceptual closure provides an interesting case study in the potential usefulness of the interactive parallel network perspective for understanding age differences in cognition. Many early studies have reported that the accuracy of identifying incomplete pictures decreases throughout adulthood, even under conditions of adequate illumination and prolonged inspection in which the contribution of peripheral sensory factors is presumably minimized. Two series of analytical studies reported by Danziger and Salthouse (1978) and Salthouse and Prill (in press) attempted to determine the reasons for these differences, but both were generally unsuccessful.

The experiments described in the Danziger and Salthouse (1978) article investigated the hypotheses that older adults perform less accurately than young adults because of differential familiarity with the stimuli, more conservative response biases, or inappropriate focus of attention. However, no evidence was found that any of these factors was responsible for the age differences observed in perceptual closure tasks. Salthouse and Prill (in press) attempted to isolate the age differences in one of four postulated processing components, but they found significant age differences favoring young adults in measures reflecting each component, thereby suggesting that the age differences were not easily localized in a single phase of processing. These

[4] Still another level of analysis is the neurophysiological level in which the factors responsible for the postulated age-related reductions in processing efficiency within networks are identified. In fact, it could be argued that speculations at higher levels are not truly explanatory in the sense that they merely refine the description of *what* is different rather than accounting for *why* it is different. There are clear limits in the degree of reductionism necessary or desirable within a given discipline, however, and no attempt will be made here to identify any more primitive mechanisms.

researchers also found comparable effects of practice and transfer in young and older adults, thus implying that the sources of the age differences are more fundamental than the processes mediated by short-term experience.

In light of this previous lack of success at localizing the source of adult age differences in perceptual closure to discrete components of information processing, it is conceivable that the differences originate because of generally less efficient processing in some type of perceptual network. That is, an age-related decrease in processing efficiency could lead to lower quality representations of the incomplete figures among older adults compared with young adults, thus hampering integration of the parts into meaningful wholes, and leading to overall poor performance in perceptual closure tasks. Moreover, age-associated variations in the efficiency of processing within a network are consistent with the existence of age differences in each postulated processing component, and in the invariance of those differences across periods of short-term practice.

The viability of the speculation that the age differences in perceptual closure originate because of a general processing inefficiency can be examined by attempting to simulate conditions analogous to perceptual closure in the network model. The plausibility of this type of interpretation can then be evaluated by using the results of the simulation manipulations as predictions of the performance of young and old adults.

Two manipulations in the simulation (involving a slightly different structure than that illustrated in Figure 1A) were considered particularly interesting in the context of identifying incomplete figures. These involved varying the percentage of Level 1 nodes relevant to a given higher level node receiving stimulation, and varying the number of time cycles during which the stimulation was present. The interest in these manipulations derives from the fact that the simulation results suggest that the young adults should benefit at least as much as the older adults by increasing the completeness of the figures or lengthening the duration of stimulus presentation. These are counterintuitive results, because in many situations older adults have been found to improve more than young adults when the task is made easier (cf. the complexity effect phenomenon discussed earlier), and yet the model predicts either that the effects should be comparable in the two age groups or that it is the young adults rather than the older adults for whom the effects of the manipulations should be greatest.

These results are illustrated in Figure 4, with untransformed maximum activation strength in the bottom panel and the logarithm of maximum activation strength in the top panel. The results are portrayed both in raw values and in log-transformed values because it is not obvious which type of scaling provides the most appropriate representation of the output. Raw scores might be preferred on the grounds that they do not contain any potentially distorting transformations, but there is considerable evidence that at least sensory magnitudes are compressed in a logarithmiclike fashion. However, there appears to be little if any evidence of transformations resulting in an expansion rather than a compression of magnitudes, and consequently the predictions from the simulation should fall somewhere along the continuum bounded by the patterns illustrated in Figure 4.

Figure 4 portrays activation of a node at Level 4 in the network for varying numbers of stimulated Level 1 nodes with slow and fast rates of propagation (the only form of efficiency limitation examined with these particular manipulations). The two propagation rates corresponded to two (intended to represent young adults) or three (intended to represent older adults) time cycles between successive propagations of activation, and the different numbers of stimulated elements reflect the average strengths with all relevant one-node patterns (e.g., 1-a, 1-b, 1-c, and 1-d), all relevant two-node combinations (e.g., 1-a + 1-b, 1-a + 1-c, 1-a + 1-d, 1-b + 1-c), and so forth. The short stimulus duration consisted of presenting stimulation for 5 time cycles, and the long duration consisted of 15 cycles of stimulation.

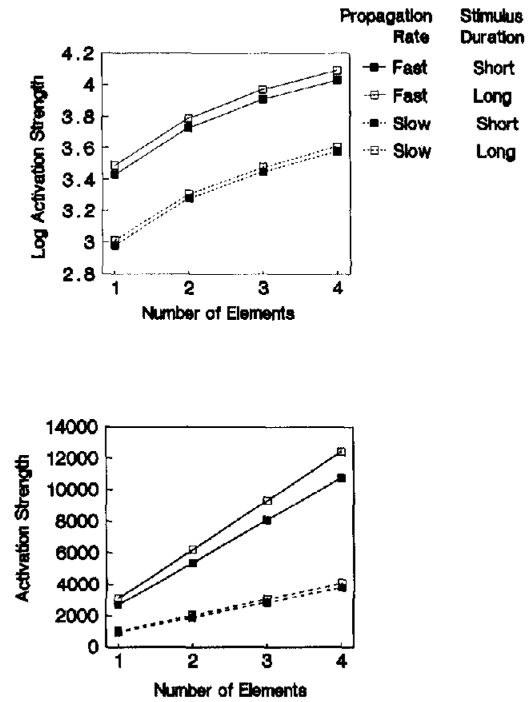


*Figure 4.* Results from the simulation at fast and slow propagation rates with stimulation directed at one to four Level 1 nodes for either 5 or 15 time cycles.

The results in Figure 4 indicate that the network simulation model predicts that older adults should not benefit more than young adults by increasing stimulus completeness or by increasing the duration of stimulus presentation. These predictions were examined by requesting young and older adults to identify images of varying degrees of completeness presented on a computer monitor for either 1 or 3 s. A total of 32 young adults (*M* age = 19.7 years) and 32 older adults (*M* age = 67.2 years) participated in the experiment, with one half of the individuals in each age group receiving the 1-s presentations and one half receiving the 3-s presentations. Every research participant received all four levels (i.e., 3%, 6%, 9%, and 12% of the picture elements) of stimulus completeness.

The major results from the experiment are illustrated in Figure 5. The most important aspect of these data is that the pattern appears similar to that illustrated in Figure 4 in that the older adults do not benefit more than the young adults with increases in either stimulus completeness or stimulus duration. As has been noted, this is opposite to what would probably have

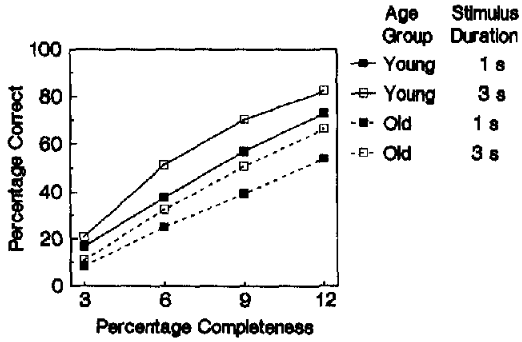


*Figure 5.* Percentage-correct picture identifications of young and older adults as a function of degree of picture completeness for 1- and 3-s presentations.

been expected by most researchers in the field, and yet it is quite consistent with the predictions from the simulation. This single finding is obviously inadequate to establish the credibility of the network model, but the apparent success of the network predictions is particularly impressive in light of the inability of previous approaches to provide a plausible account of the age differences in perceptual closure.

## Advantages and Disadvantages of Formal Models

Undoubtedly, the greatest disadvantage of attempting to develop formal models of cognitive aging phenomena at the current time is the lack of detailed knowledge about the processing actually involved in specific cognitive tasks. As it currently stands, it is impossible to derive precise predictions without making many unsubstantiated assumptions, and yet the plausibility of an explanation is often inversely related to the number of unverified assumptions. The obvious solution to this problem is additional research focused on discovery of the mechanisms responsible for performance in specific cognitive tasks. An ultimate goal is to achieve a sufficient degree of understanding to have an empirical basis for matching processing parameters in the model to particular individuals, or at least to distinct groups of individuals. Once that level of quantification is obtained, the superiority of formal models relative to the less precise informal models should become quite apparent.

A second possible disadvantage of formal models of cognitive phenomena is that it may be difficult to establish the necessity, as opposed to the sufficiency, of a particular model. That is, merely because a model can be implemented in a computational form and generates results qualitatively similar to the phenomena one wishes to explain does not mean that the model uses the same processes or mechanisms as those involved in human behavior. Although it is a considerable achievement to produce complex behavior in an artificial system, in order for that effort to qualify as a viable psychological theory, a correspondence must be demonstrated between the processes used by the model and those used by actual humans. In the area of cognitive aging, not only must the models be sufficient to reproduce (and thus account for) major cognitive aging phenomena, but there must also be empirical support for the manner in which age is represented in the model. For example, a specific model might attribute age-related stability or increases in product aspects of cognition to greater density of interconnections in the network, and age-related declines in process aspects of cognition to progressive restrictions on the number of nodes in the network that can be simultaneously active. Even though this combination of assumptions might provide a reasonable account of the major phenomena, it could only be considered speculative until there was evidence that aging was associated with changes in these particular mechanisms and not possible alternative mechanisms that might yield similar results.

An additional weakness of formal models is that it is often difficult to distinguish between the assumptions of fundamental theoretical significance and the somewhat arbitrary details necessary for implementing those assumptions in the form of a computer simulation or a mathematical expression. Moreover, because there are seldom explicit attempts to discover the robustness of the results across systematic variations in implementational details, even the original theorists may be hard pressed to identify the essential principles underlying a particular theory. Unless it is clear which assumptions are critical and which are merely expedient, however, it may be impossible to provide a definitive test of the theory.

Despite these nontrivial disadvantages of using formal modeling approaches in cognitive aging at the current time, formal models do have the tremendous advantage of substituting explicit mechanisms for vague speculations. Researchers in cognitive aging, when they are concerned about integrative mechanisms to account for age-related declines in more than a very restricted domain, often rely on hypothetical constructs such as reduced mental energy or diminished attentional capacity. Because these constructs are seldom explicitly defined (see Salthouse, in press, for a discussion), the resulting interpretations are generally not testable and, consequently, the explanations are of questionable scientific value. Implementing one's assumptions within formal models ensures that the mechanisms are clearly specified, and operation of the model allows at least their sufficiency to be evaluated.

A second major advantage of formal models of cognitive aging is that they allow investigation of the consequences of seemingly simple alterations in complex interconnected systems like the human brain. That is, only with mathematical or computer simulation models can one fully appreciate the processing consequences of shifts in critical parameters such as the quantity of available activation, the number of simultaneously active nodes, and the rate of propagating activation. For example, Figure 2 illustrates that merely slowing down the rate at which activation is transmitted to successive nodes leads to progressively larger effects at higher or more abstract levels in the network, and reduces the probability that certain nodes will ever be activated. Moreover, Figure 3 demonstrates that rate variations may have equivalent effects across different degrees of task difficulty or discriminability, and Figure 4 indicates that the rate effects are not necessarily attenuated by increasing the duration of stimlulation or the completeness of the stimuli. Although some of these results might have been predicted without implementing the assumptions in the form of a computer simulation, this mode of expression certainly facilitates the process of understanding and generating those predictions.

In conclusion, the time appears to be ripe to pursue the development of formal models to account for select phenomena in the field of cognitive aging. There are disadvantages to this approach at the present time, but most are attributable to the paucity of detailed information about the processes involved in particular cognitive tasks and how they are affected by aging. A focus on formulating and evaluating formal models may serve to channel future research in the direction of achieving the requisite information, and thus enhance knowledge about cognitive aging regardless of one's predilection for particular types of models. Finally, the benefit of providing a means of examining possible consequences of shifts in what might appear to be very simple aspects of processing clearly justifies additional interest in formal models of cognitive aging.

## References


Bowles, N. L., & Poon, L. W. (1981). The effect of age on speed of lexical access. *Experimental Aging Research, 7,* 417–425.

Bowles, N. L., & Poon, L. W. (1985). Aging and the retrieval of words in semantic memory. *Journal of Gerontology, 40,* 71–77.

Burke, D. M., & Peters, L. (1986). Word associations in old age: Evidence for consistency in semantic encoding during adulthood. *Psychology and Aging, 1,* 283–292.

Burke, D. M., White, H., & Diaz, D. L. (1987). Semantic priming in young and older adults: Evidence for age constancy in automatic and attentional processes. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 79–88.

Burke, D. M., & Yee, P. L. (1984). Semantic priming during sentence processing by young and older adults. *Developmental Psychology, 20,* 903–910.

Byrd, M. (1984). Age differences in the retrieval of information from semantic memory. *Experimental Aging Research, 10,* 29–33.

Cattell, R. B. (1963). Theory of fluid and crystallized intelligence: A critical experiment. *Journal of Educational Psychology, 54,* 1–22.

Cerella, J., & Fozard, J. L. (1984). Lexical access and age. *Developmental Psychology, 20,* 235–243.

Chiarello, C., Church, K. L., & Hoyer, W. J. (1985). Automatic and controlled semantic priming: Accuracy, response bias, and aging. *Journal of Gerontology, 40,* 593–600.

Danziger, W. L., & Salthouse, T. A. (1978). Age and the perception of incomplete figures. *Experimental Aging Research, 4,* 67–80.

Dell, G. S. (1985). Positive feedback in hierarchical connectionist models: Applications to language production. *Cognitive Science, 9,* 3–23.

Elias, C. S., & Hirasuna, N. (1976). Age and semantic and phonological encoding. *Developmental Psychology, 12,* 497–503.

Eysenck, M. W. (1975). Retrieval from semantic memory as a function of age. *Journal of Gerontology, 30,* 174–180.

Feldman, J. A., & Ballard, D. H. (1982). Connectionist models and their properties. *Cognitive Science, 6,* 205–254.

Hebb, D. O. (1942). The effect of early and late brain injury upon test scores and the nature of normal adult intelligence. *Proceedings of the American Philosophical Society, 85,* 275–292.

Hebb, D. O. (1949). *Organization of behavior.* New York: Wiley.

Hess, T. M., & Slaughter, S. J. (1986). Specific exemplar retention and prototype abstraction in young and old adults. *Psychology and Aging, 1,* 202–207.

Hinton, G. E., & Anderson, J. A. 1981. (Eds.), *Parallel models of associative memory.* Hillsdale, NJ: Erlbaum.

Horn, J. L. (1967). Intelligence: Why it grows, why it declines. *Transaction, 4,* 23–31.

Horn, J. L. (1970). Organization of data on life-span development of human abilities. In L. R. Goulet & P. B. Baltes (Eds.), *Life-span developmental psychology: Research and theory* (pp. 423–466). New York: Academic Press.

Horn, J. L. (1975). Psychometric studies of aging and intelligence. In S. Gershon & A. Raskin (Eds.), *Aging: Genesis and treatment of psychological disorders in the elderly* (Vol. 2, pp. 19–43). New York: Raven Press.

Horn, J. L. (1982). The aging of human abilities. In B. Wolman (Ed.), *Handbook of developmental psychology* (pp. 847–870). Englewood Cliffs, NJ: Prentice-Hall.

Horn, J. L., & Cattell, R. B. (1966). Age differences in primary mental ability factors. *Journal of Gerontology, 21,* 210–220.

Howard, D. V. (1980). Category norms: A comparison of the Battig and Montague (1969) norms with the responses of adults between the ages of 20 and 80. *Journal of Gerontology, 35,* 225–231.

Howard, D. V. (1983). The effects of aging and degree of association on the semantic priming of lexical decisions. *Experimental Aging Research, 9,* 145–151.

Howard, D. V., Lasaga, M. I., & McAndrews, M. P. (1980). Semantic activation during memory encoding across the adult life span. *Journal of Gerontology, 35,* 884–890.

Howard, D. V., McAndrews, M. P., & Lasaga, M. I. (1981). Semantic priming of lexical decisions in young and old adults. *Journal of Gerontology, 36,* 707–714.

Howard, D. V., Shaw, R. J., & Heisey, J. G. (1986). Aging and the time course of semantic activation. *Journal of Gerontology, 41,* 195–203.

Jones, H. E., & Conrad, H. S. (1933). The growth and decline of intelligence: A study of a homogeneous group between the ages of ten and sixty. *Genetic Psychology Monographs, 13,* 223–298.

Light, L. L., & Anderson, P. A. (1983). Memory for scripts in young and older adults. *Memory & Cognition, 11,* 435–444.

Lovelace, E. A., & Cooley, S. (1982). Free associations of older adults to single words and conceptually related word triads. *Journal of Gerontology, 37,* 432–437.

Madden, D. J. (1982). Age differences and similarities in the improvement of controlled search. *Experimental Aging Research, 8,* 91–98.

Madden, D. J. (1986). Adult age differences in visual word recognition: Semantic encoding and episodic retention. *Experimental Aging Research, 12,* 71–78.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Part 1. An account of basic findings. *Psychological Review, 88,* 375–407.

McClelland, J. L., & Rumelhart, D. E. (1985). Distributed memory and the representation of general and specific information. *Journal of Experimental Psychology: General, 114,* 159–188.

McClelland, J. L., & Rumelhart, D. E. (1986). *Parallel distributed processing: Explorations in the microstructure of cognition* (Vol. 2). Cambridge, MA: Bradford.

Mistler-Lachman, J. L. (1977). Spontaneous shift in encoding dimensions among elderly subjects. *Journal of Gerontology, 32,* 68–72.

Mueller, J. H., Kausler, D. H., & Faherty, A. (1980). Age and access time for different memory codes. *Experimental Aging Research, 6,* 445–450.

Mueller, J. H., Kausler, D. H., Faherty, A., & Olivieri, M. (1980). Reaction time as a function of age, anxiety, and typicality. *Bulletin of the Psychonomic Society, 16,* 473–476.

Petros, T. V., Zehr, H. D., & Chabot, R. J. (1983). Adult age differences in accessing and retrieving information from long-term memory. *Journal of Gerontology, 38,* 589–592.

Poon, L. W., & Fozard, J. L. (1980). Age and word frequency effects in continuous recognition memory. *Journal of Gerontology, 35,* 77–86.

Puglisi, J. T. (1980). Semantic encoding in older adults as evidenced by release from proactive inhibition. *Journal of Gerontology, 35,* 743–745.

Rumelhart, D. E., & McClelland, J. L. (1982). An interactive activation model of context effects in letter perception: Part 2. The contextual enhancement effect and some tests and extensions of the model. *Psychological Review, 89,* 60–94.

Rumelhart, D. E., & McClelland, J. L. (1986). *Parallel distributed processing: Explorations in the microstructure of cognition* (Vol. 1). Cambridge, MA: Bradford.

Rumelhart, D. E., & Norman, D. A. (1982). Simulating a skilled typist: A study of skilled cognitive–motor performance. *Cognitive Science, 6,* 1–36.

Sabbah, D. (1985). Computing with connections in visual recognition of origami objects. *Cognitive Science, 9,* 25–50.

Salthouse, T. A. (1985). *A theory of cognitive aging.* Amsterdam: North-Holland.

Salthouse, T. A. (1987a). Adult age differences in integrative spatial ability. *Psychology and Aging, 2,* 254–260.

Salthouse, T. A. (1987b). The role of representations in age differences in analogical reasoning. *Psychology and Aging, 2,* 357–362.

Salthouse, T. A. (1987c). Sources of age-related individual differences in block design tests. *Intelligence, 11,* 245–262.

Salthouse, T. A. (in press). The role of processing resources in cognitive aging. In M. L. Howe & C. J. Brainerd (Eds.), *Cognitive development in adulthood.* New York: Springer-Verlag.

Salthouse, T. A., & Prill, K. A. (1987). Inferences about age impairments in inferential reasoning. *Psychology and Aging, 2,* 43–51.

Salthouse, T. A., & Prill, K. A. (in press). Effects of aging on perceptual closure. *American Journal of Psychology.*

Salthouse, T. A., & Somberg, B. L. (1982). Skilled performance: Effects of adult age and experience on elementary processes. *Journal of Experimental Psychology: General, 111,* 176–207.

Scialfa, C. T., & Margolis, R. B. (1986). Age differences in the commonality of free associations. *Experimental Aging Research, 12,* 95–98.

Selfridge, O. G. (1966). Pandemonium: A paradigm for learning. In L. Uhr (Ed.), *Pattern recognition* (pp. 339–348). New York: Wiley.

Spearman, C. (1923). *The nature of "intelligence" and the principles of cognition.* New York: MacMillan.

Thomas, J. C., Fozard, J. L., & Waugh, N. C. (1977). Age-related differences in naming latency. *American Journal of Psychology, 90,* 499–509.

Waltz, D. L., & Pollack, J. B. (1985). Massively parallel processing: A strongly interactive model of natural language interpretation. *Cognitive Science, 9,* 51–74.

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