CHAPTER FIVE

COGNITION AND AGING: A THEORY OF NEW LEARNING AND THE USE OF OLD CONNECTIONS

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SUMMARY

This chapter describes a detailed theory of perception, production and memory for language and applies it to the problem of cognitive decline in old age. Altering a single parameter in the theory (rate of priming) was shown to account for a wide range of established age differences in cognitive ability, and to suggest an alternative framework for understanding some findings which in the past have seemed contradictory. Examples of these findings are effects of age on learning, rate of processing (general slowing), and the tip of the tongue (TOT) phenomenon.

The theory postulates different mechanisms for retrieving existing representations in memory vs. learning new or unique representations and predicts that new learning will be especially vulnerable to aging. Specifically, the theory predicts that age differences will increase with the number of new connections required in a memory task, but will diminish if already established connections are sufficient to accomplish the task. This prediction cuts across specific paradigms and theoretical distinctions and applies to a broad range of memory phenomena. By way of illustration, we review findings from experimental studies of encoding specificity, implicit versus explicit memory, and semantic versus episodic priming, and show how the observed pattern of age differences is consistent with disruption of new
learning and preservation of memory involving existing connections. The theory also makes some interesting and genuinely new predictions for future research that are spelled out here, for example, an age-linked decline in the detection of speech errors.

Psychology is currently witnessing an upsurge of interest in theory, especially within advanced areas of psychological theorizing such as cognitive psychology. However, there has been little development of theory in cognition and aging. Salthouse (1988) recently lamented this absence of theory and noted that explanations of aging effects often invoke vague concepts such as processing resources or mental effort which have not been integrated into a well defined cognitive model. Salthouse urged investigators in cognition and aging to begin development of testable and well specified cognitive models.

This recognition of the importance of theoretical development represents a recent shift in aging research and experimental psychology at large; over the past sixty years the field has been dominated by an empirical epistemology whose primary goal is to develop a body of reliable facts. Under this empirical epistemology, theories emerge spontaneously when a large enough body of data has been amassed (MacKay, 1988). However, although the accumulation of data may reveal empirical laws, it does not produce theory. Theories originate as products of cognition rather than observation. In the history of science, theorists have often developed highly successful theoretical constructs, such as atoms and sound waves, quite independently of the accumulation of experimental data (see MacKay, 1988).

Following in this spirit, the present paper analyzes selected findings in cognitive aging within the context of a detailed and explicit theory of language and memory. The theory postulates specific memory representations and processing mechanisms and views age-related memory deficits as the result of an impairment in a particular mechanism that is basic to all perception, action, and learning, namely, the priming of memory representations. Our aim is to make a theoretical contribution, rather than an empirical one, and our theoretical analyses provide an explanation for well established aging patterns such as general slowing (e.g., Birren,
1965) and differential decline in tasks involving new versus old learning or fluid versus crystallized abilities (e.g., Horn, 1982; Horn & Cattell, 1966; Light & Burke, 1988; Salthouse, 1982, 1988). Further, the theory suggests an alternative framework for understanding some existing findings which previously seemed contradictory, and it generates some interesting new predictions for future research.

The theory presented is the Node Structure Theory (NST) developed originally by MacKay (1982; 1987) to provide a general and explicit account of the perception and production of language and other cognitive skills. The theory has been extended here to include processes that are rarely seen in models of language perception and production, but are necessary for explaining memory phenomena such as the recall of new information (see also MacKay, 1990). The theory likewise incorporates processes that are rarely seen in memory models, but are necessary for other reasons, for example, producing speech sounds in correct order in words, and words in correct order in sentences.

This chapter is organized into seven sections: Section I presents a brief qualitative description of the basics of the NST, focusing on the representation and use of already established knowledge. Section II outlines the Transmission Deficit hypothesis, the claim that priming transmitted across connections between nodes in the NST declines in rate and amount as a function of age. Section III shows how this Transmission Deficit explains general slowing, the reduction in processing rate that accompanies aging. Section IV examines the differences between two types of learning processes in the NST: commitment learning, the process whereby new connections are formed or new combinations of familiar information are represented versus engrainment learning, the process whereby existing connections among familiar information are strengthened when the information is retrieved or utilized. We show that under the Transmission Deficit hypothesis, commitment learning should be much more vulnerable to the effects of aging than engrainment learning. Using this principle, Section V provides an account of older adults' pattern of impaired and spared memory functions seen in studies of encoding specificity, semantic versus episodic priming, and direct versus indirect memory tasks.
Section VI examines a striking exception to this general pattern, namely, the age-related increase in tip of the tongue (TOT) states in which retrieval of existing word knowledge is impaired. We show how the Transmission Deficit hypothesis can explain this specific deficit. Finally, Section VII outlines some new and untested predictions concerning the relation between aging and phenomena such as error detection that follow from the Transmission Deficit hypothesis.

**BASICS OF THE NODE STRUCTURE THEORY**

Mental processes in the NST consist of inhibitory and excitatory interactions occurring in parallel between hypothetical processing units or nodes in a highly interconnected network. Like the parallel distributed processing (PDP) models of McClelland and Rumelhart (e.g., Rumelhart & McClelland, 1986) the model allows simultaneous integration of many sources of information. However, nodes within the NST involve local representation (where a unique concept corresponds to a single node) rather than the mass action representation of some PDP models (where a unique concept corresponds to a pattern of activity among a large number of nodes, and no node codes any concept uniquely).

Some NST nodes represent higher level cognitive components such as phonological segments, syllables, and words, and play a role in both perception and production. These "mental nodes" are organized hierarchically into a sentential or semantic system that represents semantic and grammatical information, and into a phonological system for speech perception/production, and an orthographic system for reading/writing (see Figure 1). Other systems do not share perception/production functions. For example, one system contains sensory analysis nodes which represent patterns of auditory input for perceiving speech. Another system contains muscle movement nodes which represent patterns of muscle movements for producing speech.

For purposes of illustration, Figure 2 shows a sample of top-down connections for producing the sentence "The dragon ate the fudge." The highest level node representing the entire thought underlying the sentence has the content "the dragon ate the fudge."
This particular node is connected to two other nodes: One represents the thought "the dragon" and the other represents the thought "ate the fudge". The node representing "the dragon" is connected to two lexical nodes: one represents "the" and the other represents "dragon". Nodes such as these are part of the sentential-semantic system, and will be the primary focus of the present paper because most of the memory phenomena discussed here occur.
Figure 2: A sample of top-down connections for producing the sentence

The dragon ate theudge.

MucKAY and BURKE
within this system. Note, however, that lexical nodes are connected with specific phonological nodes organized hierarchically into syllables, phonological compounds, segments, and features. Activation of these nodes allows retrieval of the phonology of the word corresponding to the concept activated at the lexical level. The phonological nodes map onto a system of nodes assumed to underlie muscle movements so that the person could actually speak the word or sentence, not just think it. (See MacKay, 1987, for details of node structures within the phonological and muscle movement systems).

Nodes exhibit four processing characteristics that are relevant here: Activation, priming, linkage strength, and self-inhibition. Node activation in the NST differs from the concept of spreading activation in other network theories (e.g., Anderson, 1983; McClelland & Rumelhart, 1985). Node activation never spreads, is all-or-none in nature, and has potential behavioral consequences: activation of the appropriate nodes results in perceptual recognition and/or production of a word. An activated node simultaneously primes all nodes connected to it and a primed node sends priming to its connected nodes with degree of priming decreasing as a function of distance. However, priming differs from the concept of spreading activation in other network theories. Priming prepares a node for possible activation, and a node must be primed first before it can be activated. Figure 3 illustrates the priming and activation of a node. Although priming summates spatially and temporally, it only summates up to an asymptote, and cannot by itself activate a node: a special activating mechanism is required for activation. Linkage strength determines how much and how rapidly priming crosses the connections. Linkage strength represents a relatively long-term characteristic of a connection and has been used to explain a wide range of practice effects: Highly practiced connections have greater linkage strength and therefore transmit priming more rapidly and up to a higher asymptotic level than do relatively unpracticed connections (MacKay, 1982). Another factor influencing linkage strength is recency of activation: all other factors being equal, linkage strength will be greater for connections between nodes that have been recently activated. Conversely, connections between nodes that have not
been activated over long periods of time (years) will exhibit diminished linkage strength.

After a node becomes activated, it undergoes a brief period of self-inhibition during which its level of priming falls below normal or resting level (see Figure 3). The mechanism underlying self-inhibition is an inhibitory 'satellite'. After receiving sufficient priming from its activated parent node, the satellite becomes activated and inhibits its parent node.

The nodes discussed so far are known as content nodes, because they represent the form or content of a memory representation. We turn now to sequence nodes, the mechanisms for activating content nodes. Sequence nodes connect with a set of content nodes called a sequential domain, and all content nodes belong to at least one sequential domain. Nodes in a sequential domain all share the same sequential privileges of occurrence. For example, nodes in the semantic system that are in the same sequential domains, e.g., color adjectives, exhibit identical patterns of sequential occurrence in a sentence. By way of illustration, sequential domains for the content nodes in Figure 2 are indicated in parentheses; the node representing the thought "the dragon" is in the noun phrase domain, "ate the fudge" is in the verb phrase domain, "the" is in the determiner domain, and "dragon" is in the noun domain.

Once a sequence node becomes activated, it repeatedly multiplies the priming of every node in its domain by some large factor within a relatively brief period of time. This multiplicative process has no effect on an unprimed node, but soon serves to activate (that is, bring to threshold) the content node with the greatest degree of priming in the domain. Normally, the one node with more initial priming than all other nodes in the domain will reach threshold first, and this "most-primed" node will become activated. Thus, the all-or-none nature of activation and the control of activation by sequence nodes allow production of responses in appropriate order, for example, correct sequencing of words in sentences. Once a content node becomes activated, it inhibits its corresponding sequence node, thereby ensuring that one and only one content node in a domain becomes activated at any one time.
The priming, activation and recovery functions for a single node. Activation is achieved through a special activating mechanism which multiplies the priming of all nodes within a sequential domain so that the first node to reach threshold is activated.

THE TRANSMISSION DEFICIT HYPOTHESIS

The Transmission Deficit hypothesis provides the basis for explaining effects of aging within the NST. Under the Transmission Deficit hypothesis, age weakens the linkage strength of connections between nodes in the network so that the rate and asymptotic amount of priming transmitted across any given connection declines as a function of age. From a historical point of view, this Transmission Deficit account of aging is not entirely new: To explain the word finding problems of older adults, Bowles, Obler and Poon (1989) and G. Cohen and Faulkner (1986) proposed an age-related reduction in transmission of priming from semantic to phonological representations. And Salthouse (1988) can be interpreted as suggesting the possibility of a more general reduction in the rate of priming as one of three possible explanations for
observed declines in new learning and fluid intelligence. The other explanations involved either a decrease in how many nodes can be simultaneously active, or a decrease in the maximum available activation (see also Salthouse, 1985). However, the NST postulates no principled limit on how many nodes can be simultaneously primed and/or activated, and views activation as a local or localized activity (that is specific to particular nodes) rather than a global or network resource that can become depleted. Moreover, the NST views aging as just one of several factors contributing to transmission deficits in both young and older adults, others being recency of activation (time since last activation) and history of prior practice (number of previous activations over the course of a lifetime). Finally, the NST allows greater specificity about the nature of transmission deficits in particular connections and the implications of these deficits within a detailed account of perception, production, and recall in language and other cognitive skills.

Figure 4 illustrates the specific form of the age-linked transmission deficit by comparing the transmission of priming across a single connection to a YOUNG versus an OLD node. The YOUNG and OLD nodes are part of an otherwise comparable domain of nodes with spontaneous or resting level \( L_0 \), and both are receiving priming transmitted from a single other node beginning at time \( t_0 \) and ending at time \( t_g \). All other characteristics of the nodes are assumed to be equal in the theory, especially their history of prior practice and their recency of activation. The summation characteristics of the nodes in Figure 4 illustrate how priming summates over time until asymptote is reached, and as can be seen there, priming builds up more slowly and to a lower asymptote for OLD versus YOUNG nodes. Figure 4 also shows how the priming on a node decays over time when a connection no longer transmits priming. Note that decay rate is unrelated to age under the Transmission Deficit hypothesis: priming decays at the same rate for YOUNG versus OLD nodes.

Because frequent and recent use (activation) also influence linkage strength and enable more efficient transmission of priming across connections, these factors can in principle mask an age-linked transmission deficit in older adults. In general,
However, effects of frequency and recency of activation seem likely to trade off or cancel one another with advancing age. Frequency-of-use (repeated activation of already coded information) can only increase with age, whereas recency-of-use will tend to decrease with age. As Burke, Worthley, and MacKay (1989) point out, age provides greater opportunity for long intervals following, say, last use of the name of an acquaintance such as a grade school teacher. Such decreases in recency-of-use may explain why older adults experience disproportionately more TOTs for the names of acquaintances (see Burke et al., 1989).

The Transmission Deficit hypothesis is consistent with neurobiological characteristics of aging. An example is the observation of Landfield (1988) and Landfield and Lynch (1977) that neurons in the aged hippocampus (of rats) exhibit reduced potentiation and increased time to peak. The Transmission Deficit hypothesis is also consistent with the finding that the time required for conducting neural activity between brain structures, including different areas within the cortex, increases with age (see e.g., Aston-Jones, Rogers, Shaver, Dinan & Moss, 1985; Dorfman & Bosley, 1979; Streng & Hedderich, 1982). Under the Transmission Deficit hypothesis, this age-linked increase in conduction time may reflect increased synaptic delays, a possibility that remains to be tested in the case of cortical neurons. The exact nature of such synaptic delays also remains to be determined, with possibilities including reduced postsynaptic responsivity and decreased uptake of neurotransmitter substances (see Decker, 1987).

The remainder of the present paper elaborates on various consequences of the Transmission Deficit hypothesis illustrated in Figure 4. One consequence explored in Section III is reduced reaction times and rates of responding in a wide variety of tasks. Another consequence is that OLD nodes will sometimes transmit insufficient priming to enable their connected nodes to become activated. This consequence may underlie the age-linked deficits in the encoding of new information: Section IV and V argue that transmission deficits can make the learning of new information impossible by causing activation failures in the uncommitted nodes that are essential for coding new information. Section VI argues that transmission deficits also cause activation failures in
Figure 4. The Transmission Deficit hypothesis: The hypothetical functions for the summation and decay of priming over time for a YOUNG and an OLD node within an otherwise comparable domain of nodes with spontaneous or mean noise level \( L_0 \). Both nodes are receiving priming transmitted from a single other node beginning at time \( t_0 \) and ending at time \( t_3 \) (see text for explanation). Summation characteristics illustrate how priming builds up on these nodes over time up to asymptote, while decay characteristics illustrate how priming decays over time to the spontaneous or mean noise level.
existing connections and are responsible for retrieval failures such as TOTs.

**GENERAL SLOWING UNDER THE TRANSMISSION DEFICIT HYPOTHESIS**

The Transmission Deficit hypothesis readily explains the general slowing that occurs with aging in a wide range of tasks (for a summary, see e.g., Salthouse, 1985). However, the relation between slowing and transmission deficits is neither simple nor direct under the NST and requires a clear understanding of the age-related decrement in priming transmission illustrated in Figure 4. Implications of this decrement are discussed below.

**How Priming Transmission Influences Speed and Errors in the NST**

Under the NST, both reaction time and general rate of output depend on how soon following onset of priming a triggering mechanism (sequence node) is applied to a domain for the full set of nodes in an output hierarchy. That is, a triggering mechanism can be applied to its domain at any voluntarily determined point in time after onset of priming ($t_0$ in Figure 4) for every node in an output hierarchy. If the triggering mechanism is applied soon after onset of priming, say at $t_1$ in Figure 4, the overall rate of output will be fast because activation of each of the many hundreds of nodes in the output hierarchy will occur soon after priming onset. (Recall that the nodes illustrated in, for example, Figure 2 represent only a small subset of the total number of nodes in such an output hierarchy). However, if the triggering mechanism is applied long after onset of priming, say at $t_2$ in Figure 4, the overall rate will be slow, because activation of each of the nodes in the output hierarchy will occur longer after priming onset.

Consider now the relation between rate and errors in the theory. For a given priming function, the faster the rate (that is, the sooner the triggering mechanism is applied after the content node begins to receive priming), the greater will be the likelihood of error (that is, the probability of activating the wrong content node). This is
because the target node is less likely to have greater priming than all other extraneous nodes in the domain (the current noise level) soon after priming onset as compared to later (see Figure 4). Or equivalently in the theory, the more rapid the priming summation characteristics of nodes, the faster will be the potential rate of output for any given probability of error. In particular, with probability of error held constant, the overall rate of output can be faster for YOUNG nodes than for OLD nodes because of the more rapid priming summation characteristics of YOUNG nodes (see Figure 4). However, the theory does not necessarily assume that young and older adults are equally intolerant of errors, that is, that they adopt equivalent error criterions. For both young and older subjects it is possible to vary the error criterion within wide limits: all subjects can reduce the probability of errors by decreasing speed or they can increase the rate of output at the expense of allowing more errors.

To illustrate these points more concretely, let the YOUNG and OLD nodes in Figure 4 represent the concept blue (color adjective) for young and old adults participating in a standard Stroop task. The stimulus in this hypothetical experiment is the word "red" printed in blue ink, and the subject must name the color of the ink, that is, produce the word "blue" as quickly as possible in this example. Now in order for the correct response to be produced, blue (color adjective) must acquire more priming than any other node in the color adjective domain so as to become activated under the most-primed-wins principle. In particular, blue (color adjective) must acquire more priming than red (color adjective), its main competitor in the color adjective domain. Now, red (color adjective) automatically acquires priming bottom-up from the orthographic characteristics of the word, and because of the frequency with which we read words such as red (see MacKay, 1987), this priming rises very rapidly to an asymptotic level that can be considered a theoretical constant corresponding to, say, $L_1$ in Figure 4. The color of the letters simultaneously primes blue (color adjective), but this priming accumulates more slowly because we relatively rarely name the color of letters (see MacKay, 1987). This more slowly but systematically increasing priming level will exceed $L_1$ by time $t_1$ for the YOUNG node in Figure 4, and by time $t_2$ for the OLD node.
Thus, because an activating mechanism always activates the most primed node in its domain, blue (color adjective) will be activated and the output will be error-free if the activating mechanism is applied after $t_1$ for the YOUNG node and after $t_2$ for the OLD node. More specifically, if young and older subjects both adopt an error criterion corresponding to, say, $L_1$ in Figure 4, rate of output will be faster for YOUNG nodes (inversely proportional to $t_1$ in Figure 4) than for OLD nodes (inversely proportional to $t_2$).

Turning to the accuracy side of the speed-accuracy trade-off (SAT) function, subjects will produce the prototypical Stroop error, "red" instead of "blue" in this example, if they apply their activating mechanisms before $t_1$ for YOUNG nodes in Figure 4 and before $t_2$ for OLD nodes. The substitution of "red" for "blue" in this example represents an error occurring at the lexical level within the semantic-sentential system, but the underlying principles can be generalized to apply to a wide range of error types within any arbitrarily chosen domain at all levels of the system.

To better illustrate this generalizability, if nodes other than the correct node in a domain are labeled extraneous nodes, then the noise level or degree of priming arriving at the most primed extraneous node in the domain can in general be considered to assume a Gaussian distribution with mean $L_0$ (the spontaneous or resting level) at any given point in time (see Figure 5). For example, the noise level represented as $L_1$ in Figure 4 might exceed the spontaneous or mean resting level of other extraneous nodes in the domain by, say, 3 standard deviations because of priming received from 'other sources', here the nodes coding the orthography of the word "red". In general, however, the noise level (priming of the most primed extraneous node) can be considered a random variable at any point in time, whereas priming for the correct node will increase systematically over time in the manner shown in Figure 4. As a consequence, the later the application of the triggering mechanism following onset of priming, the lower will be the probability of error up to the asymptote of a given priming function. In short, errors will trade off with speed in the theory and speed-accuracy trade-off functions for YOUNG vs. OLD nodes should resemble the priming functions in Figure 4, a prediction that is readily subjected to experimental test (see e.g., Wickelgren, 1977).
Time and errors are closely coupled under the NST: choosing a particular rate is equivalent to choosing a particular probability of error and vice versa. Priming transmission plays a universal role in determining what time-error criterion can be adopted because increased priming transmission causes a favorable shift in the absolute values that any time-error criterion can assume (see Figure 4). Also, many cognitive and motivational factors undoubtedly play a role in what time-error criterion an individual will in general select, and a given individual may alter their time-error criterion depending on the situation or occasion. However, we can assume that people normally choose a conservative time-error criterion: a rate of output resulting in some acceptably low probability of error.

**COMMITMENT LEARNING UNDER THE NST**

So far, we have been discussing the activation of information that is already represented in memory, the so called *committed*
nodes in the NST. Connections to a committed node are usually strong enough so that the committed node can accumulate sufficient priming to enable activation when its activating mechanism (sequence node) is applied. For example, adults would normally have committed nodes representing already encountered lexical concepts such as "clumsy" and "bear" in Figure 6. These committed nodes engage in a form of learning known as engrainment learning that provides the basis for effects of frequency or practice (repeated activation). Engrainment learning occurs when practice increases the linkage strength of connections between committed nodes in the model, and enables greater speed and accuracy in executing established behaviors.

New learning, however, requires a different type of node, the so-called uncommitted nodes, and an additional type of learning mechanism. Unlike a committed node, an uncommitted node receives connections that are so weak that it cannot accumulate enough priming to become activated when its activating mechanism is applied, even in young adults. Connections from uncommitted nodes are likewise so weak that they transmit too little priming for connected nodes to become activated when their activating mechanism is applied. Commitment is therefore a property of both nodes and of connections.

New learning occurs to the extent that an uncommitted node becomes committed, a process that requires prolonged activation and is called commitment learning. For example, no pre-established node represents the phrase "clumsy bear" in Figure 6, but only the uncommitted node labeled X. This is true for a person who has not experienced or processed this particular noun phrase before, or at least not to the extent required for permanent commitment learning. Thus when the NOUN PHRASE sequence node becomes engaged, none of the nodes in its domain have sufficient priming to become activated; inhibition of the sequence node occurs only when there is activation. As a result, there is sustained activation of the sequence node, which activates the binding node for noun phrases. (Each sequence node has a corresponding binding node that binds or commits nodes of that type.) Sustained activation also triggers orienting reactions, that
include behavioral components, such as the inhibition of ongoing activity (see MacKay, 1990).

Bindings nodes operate as follows. When activated, a binding node shuts down the inhibitory satellite of all content nodes to which it is connected, in the present example, all noun and adjective nodes. With inhibition shut off, nodes that happen to be activated at the time remain activated for a prolonged period of time, allowing priming to summate at the uncommitted node for a longer period. This summation of priming may eventually enable the uncommitted node to achieve sufficient priming so that it can become activated as the most primed in the domain when its activating mechanism is applied. Activating the uncommitted node in turn causes a slight but relatively long-term increase in linkage strength across its connections, resulting in "weak commitment" of the uncommitted node. Weak commitment is extremely fragile, however: unless weakly committed nodes become activated again within some relatively brief period of time, the
increased strength of their connections can decay over time so that the node reverts to uncommitted status.

Commitment Learning and the Transmission Deficit Hypothesis

Strong transmission of priming is essential for the retention of new information or novel combinations of old information in the NST account of commitment learning discussed above. If prolonged activation of the novel combination of committed nodes fails to deliver priming to the uncommitted node in sufficient strength, activation and commitment of the uncommitted node cannot occur. This means that if aging reduces priming transmission, as postulated under the Transmission Deficit hypothesis, then uncommitted nodes in older adults will fail to achieve even weak commitment, and commitment learning will fail to occur.

As a result, memory for new information will suffer greater age-related deficits than memory for old or committed information because commitment learning requires considerably more summation of priming than does retrieval of old information. Moreover, certain characteristics of committed nodes can compensate for an age-linked reduction in priming. In particular, practice involving already committed nodes is likely to increase with age and by increasing linkage strength, this additional practice would reduce the effect of an age-related transmission deficit. Further, the complex connections among committed nodes within the semantic system are likely to overcome an age-linked transmission deficit via convergent priming. For example, under the NST, associated concepts such as doctor and nurse are linked via connections to a large number of proposition and predicate nodes representing information such as "doctors and nurses work in hospitals", "...wear white uniforms", "...give injections", etc. Consequently, priming will converge on the committed nodes for such concepts from these multiple connections, enabling summation of priming that reduces the effect of a transmission deficit (see discussion of semantic priming effects and the single source factor below).
Selective Impairment of Binding Nodes: An Alternative to the Transmission Deficit Hypothesis

The Transmission Deficit hypothesis is not the only means of predicting age-related deficits in the learning of new information under the NST. The hypothesis that aging selectively impairs the functioning of binding nodes represents a viable alternative. Because binding nodes are essential for commitment learning, this "Binding Impairment hypothesis" makes the same predictions as the Transmission Deficit hypothesis: age-related impairments will be most pronounced when new information or novel combinations of old information must be retained. Moreover, as MacKay (1990) points out, a Binding Impairment hypothesis is consistent with the pattern of amnesic effects that result when hippocampal and mediotemporal areas of the brain are damaged or lesioned.

However, the Binding Impairment hypothesis faces a large number of unresolved theoretical issues that led us to abandon it in favor of the Transmission Deficit hypothesis as an explanation of age-related effects. One unresolved theoretical issue is why aging impairs the functioning of binding nodes but not the functioning of other closely connected nodes such as sequence and content nodes. Another unresolved issue concerns the explanation of aging effects in tasks that do not involve novel information, for example, the general slowing effects discussed above, and the TOT phenomenon (see below). A final unresolved issue for a Binding Impairment hypothesis is the specification of precisely how the functioning of binding nodes could be impaired. For example, does aging influence how long a sequence node can sustain its activation so as to trigger its binding node? Or functionally equivalent under the NST, does aging somehow decrease the responsivity of binding nodes, thereby increasing the threshold that must be reached in order to activate a binding node? Or does aging selectively decrease how effectively a binding node inhibits its domain of inhibitory satellites, thereby interfering with the prolonged activation required for commitment?

These various versions of the Binding Impairment hypothesis all share an additional drawback: they predict lapses of consciousness because binding nodes introduce prolonged
activation, which corresponds to awareness in the NST (see MacKay, 1990). If age impairs the functioning of binding nodes, prolonged activation would fail to occur, so that awareness or consciousness of new information should diminish with age. However, neither diminished awareness nor disturbances of ongoing consciousness seem characteristic of normal aging.

COMMITMENT LEARNING AND AGE DIFFERENCES IN MEMORY PERFORMANCE: A SELECTIVE REVIEW

As incorporated within the NST, the Transmission Deficit hypothesis predicts greater age-related impairments when commitment learning is involved. Thus, the theory accounts for one of the most striking characteristics of the memory deficit in older adults: the extent to which the deficit involves memory for new rather than old information (e.g., Light & Burke, 1988; Salthouse, 1985). For example, in evaluating the contribution of age and experience to chess performance, Charness (1985) concludes that age differences are seen when new information must be represented, but not when well-practiced information is involved. Further, relative to young adults, older adults improve more slowly with practice on tasks involving new learning, but their rate of improvement is at least as fast on familiar tasks (Welford, 1985).

The NST uses a single principle, called here the "commitment learning principle", to account for the pattern of age-related memory deficits in a wide variety of experimental paradigms. Under the commitment learning principle, age deficits will increase with the amount of commitment learning required for accurate performance. To illustrate how the commitment learning principle can be applied to specific experimental situations, we analyze age effects in three well-known memory paradigms: encoding specificity tasks, episodic versus semantic priming tasks, and direct versus indirect memory tasks. We provide an account of these findings using a single principle rather than the variety of different mechanisms called for in the original studies.
Encoding Specificity, Aging, and the Commitment Learning Principle

One approach to investigating the representation of new memories has been to evaluate the effectiveness of different types of retrieval cues. According to the encoding specificity principle (Tulving & Thomson, 1973), effectiveness of a cue at retrieval depends on the extent to which it is encoded in the representation of the target material. Thus under the NST, encoding specificity depends on the strength of connections between nodes representing the retrieval cue and the target, that is, on how much priming can be transmitted between them. If retrieval cues require the formation of new connections to the target, that is, commitment learning, these cues should be more effective for young than older adults according to the commitment learning principle. If retrieval cues require only existing connections, that is, engrainment learning, these cues should be about equally effective for young and older adults.

The commitment learning principle is consistent with the findings of Craik and Simon (1980) who gave subjects sentences and tested for recall of a target noun (e.g., "bear") after supplying as a retrieval cue either the original adjective from the sentence (e.g., "clumsy") or the name of a superordinate category for the noun (e.g., "animal"). For the young but not the old, the adjective produced better recall than did the category (see Table 1). Similarly, Rabinowitz, Craik, and Ackerman (1982) gave subjects word pairs that were either strongly associated (e.g., "king-queen") or weakly associated (e.g., "whiskey-water"); see Table 1). Retrieval cues for the second word in each pair were either the same word studied in the pair or a different word which varied in its strength of association to the target. For young but not older adults, the original word studied in the weak pair (Same-Weak) produced better recall than a different but strongly associated word (Different-Strong). Consistent with the commitment learning principle, the age decrement was about twice as large in the Same-Weak condition compared to the Same-Strong condition in which retrieval cues depended on established connections.
Table 1

Examples of Stimuli and Results from Encoding Specificity Studies

<table>
<thead>
<tr>
<th>Study</th>
<th>Retrieval Cue</th>
<th>Encoding Cue Identity: Same</th>
<th>Different</th>
<th>Same</th>
<th>Different</th>
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<tbody>
<tr>
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<tr>
<td>Study: The highlight of the circus was the clumsy BEAR.</td>
<td>Retrieval cue</td>
<td>Original (e.g., clumsy)</td>
<td>Different (e.g., animal)</td>
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<td>Rabinowitz, Craik &amp; Ackerman (1982)</td>
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<td>Study: king-QUEEN (Strong); whiskey-WATER (Weak)</td>
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<tr>
<td>Young</td>
<td>.92&lt;sup&gt;a&lt;/sup&gt;</td>
<td>.07</td>
<td>.85</td>
<td>.68</td>
<td></td>
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<tr>
<td>Old</td>
<td>.83</td>
<td>.03</td>
<td>.62</td>
<td>.63</td>
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<tr>
<td>Hess &amp; Higgins (1983)</td>
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<td>Study: river bank shore</td>
<td></td>
<td>Same</td>
<td>Different-Related (e.g., money bank check)</td>
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<tr>
<td>Young</td>
<td>.92&lt;sup&gt;b&lt;/sup&gt;</td>
<td>.80</td>
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<td>Old</td>
<td>.71</td>
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<sup>a</sup> Data are mean cued recall
<sup>b</sup> Data are mean correct recognition
Under the NST, the effectiveness of the adjective in the Craik and Simon (1980) study and of the weak associate in the Rabinowitz et al. (1982) study depended on commitment of new connections between the retrieval cues and their respective target words. In contrast, category cues in the first study and strong associates in the second study depended on engrainment learning that strengthens the already existing connections between cue and target. Thus older adults' apparent deficit in encoding specificity is best understood as an impairment in commitment learning relative to engrainment learning. This difference between commitment and engrainment learning is illustrated in Figure 7. In order for *clumsy* to be an effective retrieval cue for *bear*, the uncommitted node labeled "X" which represents the connection between *clumsy* and *bear* must become committed. However, the category name in the first study would, according to the model, be connected to the target word by an already committed node, in Figure 7, *bear* is an *animal*. Older adults did relatively better with this second type of retrieval cue because no nodes had to become committed for *animal* to call up *bear*.

Regardless of the retrieval cue, memory that a word such as *bear* was presented in an experiment requires commitment learning under the NST, in the present example, an association between *bear* and some representation of the experimental context, simplified in Figure 7 as was presented.\(^1\) An uncommitted node \(X'\) represents this connection between target and experimental context, and this, according to the commitment learning principle, would explain the age decrement obtained by Rabinowitz et al. (1982) with the Same-Strong retrieval cue.

An alternative account of these findings postulates that age differences in encoding specificity reflect declines in "processing

\(^1\) Such episodic knowledge requires a connection to nodes representing the context of the experience, and may be represented in the semantic-sentential system as, for example, a proposition that the concept "bear" was presented via computer terminal, or in a visual imagery system, as, for example, a visually based representation of the computer display or of the appearance of the experimental room. Representations for specific episodes are clearly varied and complex and may include information about time of occurrence, location, modality, and other unique aspects of the episode (Burke & Light, 1981). However, an exhaustive analysis of episodic knowledge representations is not the goal of the present paper.
resources" in old age (e.g., Craik, 1983; Rabinowitz et al., 1982). For example, Rabinowitz et al. (1982) concluded that older adults resorted to "general" encoding in the Same-Weak condition because limited processing resources prevented encoding of the specific context. This alternative account is weakened on a theoretical level by the amorphousness of the processing resources concept (see Light & Burke, 1988; Salthouse, 1988), and on an empirical level by the finding that older adults show context specific encoding when new
information is not involved, as in, for example, a series of studies by Hess and his colleagues (see also Burke & Harroid, 1988).

Subjects in Hess (1984) and Hess and Higgins (1983) studied homophones paired with one or two words related to one of the homophone's meanings. An example is shown in Table 1. Both young and older adults recognized homophones better with the original context words rather than with different context words related to the other meaning of the homophone target. This finding suggests that the original context words influenced encoding of the homophone meaning and thus is inconsistent with the hypothesis that older adults only engage in "general" encoding. With general encoding, homophone recognition should have been the same for the original and different context words: encoding at study would be independent of specific context and thus would involve one of the two general meanings of the homophone with equal probability (assuming they were equally available). Under the NST, however, the effect of the context words on the homophone should be unimpaired for older adults because the homophone and context words are semantically related and have pre-established connections that can be strengthened through enactment learning. Older adults' recognition did in fact show a decrement compared to young adults' of about the same magnitude in both conditions because new connections to the experimental context were required in both conditions and this commitment process exhibits age-related impairment under the commitment learning principle.

Finally, when subjects studied target words with an unrelated context word, young but not older adults had better recognition of the target with the original unrelated context word rather than a changed context word (Hess, 1984). Here contextual effects depend on establishment of new connections and the fact that the original context failed to improve older adults' recognition is consistent with the commitment learning principle.

Semantic versus Episodic Priming Effects

It is well established that a target word (e.g., doctor) can be processed more rapidly when it is immediately preceded by a
Studies of Semantic Priming in Young and Older Adults

<table>
<thead>
<tr>
<th>Authors</th>
<th>Task</th>
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<tbody>
<tr>
<td>Balota &amp; Duchek, 1988</td>
<td>pronunciation (SOA)</td>
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<td>Bowles &amp; Poon, 1985</td>
<td>lexical decision</td>
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<tr>
<td>Burke, White &amp; Diaz, 1987</td>
<td>lexical decision (SOA; Auto-Atten)</td>
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<td>Burke &amp; Yee, 1984</td>
<td>lexical decision</td>
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<td>Cerella &amp; Fozard, 1984</td>
<td>pronunciation</td>
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<td>Chiarello, Church &amp; Hoyer, 1985</td>
<td>lexical decision</td>
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<td>G. Cohen &amp; Faulkner, 1983</td>
<td>lexical decision</td>
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<td>Howard, 1983</td>
<td>exical decision</td>
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<td>Howard, Lasaga &amp; McAndrews, 1980</td>
<td>Stroop task</td>
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<td>Howard, McAndrews &amp; Lasaga, 1981</td>
<td>lexical decision</td>
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<tr>
<td>Howard, Shaw &amp; Heisey, 1986</td>
<td>lexical decision (SOA; Auto-Atten)</td>
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<td>Madden, 1986</td>
<td>lexical decision</td>
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<td>Madden, 1988</td>
<td>lexical decision</td>
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<tr>
<td>Nebes, Boller &amp; Holland, 1986</td>
<td>pronunciation</td>
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Note: Studies are indicated that varied stimulus-onset-asynchrony (SOA) between prime and target and/or attempted to isolate automatic and attentional activation (Auto-Atten).

A semantically associated word (e.g., nurse). This speeding of response time in, for example, lexical decision or pronunciation tasks has been called the semantic priming effect because it is believed that its source is a spread of activation from the prime word to representations that are associated in memory, temporarily increasing their accessibility (e.g., Collins & Loftus, 1975). A number of studies (see Table 2) have demonstrated that this "semantic priming" effect is at least as large in older as young adults. This holds for studies that were designed to detect age
differences in the speed of semantic priming by varying stimulus onset asynchrony (SOA), the temporal interval between prime and target, and in automatic versus attentional priming. The one exception to this is Howard, Shaw and Heisey (1986) who found significant semantic priming effects for young but not older adults at their shortest SOA, 150 ms. Other studies, however, have provided no evidence for age differences in speed of semantic priming (Balota & Duchek, 1988; Burke, White & Diaz, 1987).

The fact that semantic priming effects remain constant with age is consistent with the commitment learning principle because semantic priming involves existing rather than new connections. Activation of the prime results in the spread of priming via the many already established connections between related words, which can then be activated more rapidly. Under some conditions, however, there should be small age differences in priming of established nodes because the Transmission Deficit hypothesis postulates age-linked declines in rate or amplitude of priming. There are several reasons why within the NST such age differences are not seen in semantic priming studies. First, age deficits would be more apparent with single rather than multiple sources of priming (see below). Within the semantic system many connections link nodes to one another (see also Jones, 1985) and multiple sources of priming diminish the likelihood of demonstrating Transmission Deficit. Further, the speed and amount of priming transmitted depends on the linkage strength of the connections. Linkage strength increases with practice (see MacKay, 1982) and older adults have accumulated more practice than younger adults with common words such as doctor and nurse and their interrelations (the connections between them). According to the commitment learning principle, the engrainment learning process resulting from practice is relatively unimpaired by aging.

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2 Intuitively one might think that practice effects for common words would asymptote at some point with age, ruling out the possibility of further age-linked practice effects for such words as doctor and nurse. However, the effects described here depend on the interrelations between words via connections to predicate nodes representing concepts such as "work in hospitals" and "give injections". Unlike low level phonological nodes, these proposition and predicate nodes are extremely unlikely to acquire asymptotic levels of practice, even over the lifespan of older subjects.
Consistent with this, the rate of improvement with practice for a variety of already established behaviors is similar across age (see Charness, 1985; Welford, 1985). Thus, older adults' greater linkage strength for common words and the connections between them would tend to offset an age-linked Transmission Deficit.

However, even if transmission of semantic priming in fact varies with age, this paradigm may be insufficiently sensitive for demonstrating such an age difference. Older adults typically have longer absolute response times than young adults, providing a longer time interval during which priming can spread from the prime to the target, even when the prime-target SOA is controlled. This longer interval from prime presentation to target response could compensate for a slower rate of priming in older adults (see Howard, 1988a). A more accurate picture of the time course of processing may be gained by using a deadline procedure in which subjects are induced to respond at particular points in time after presentation of the target (cf. Wickelgren, 1977; McClelland, 1979).

In short, an analysis of the semantic priming paradigm within the NST suggests that this paradigm is a difficult testing ground for the Transmission Deficit hypothesis.

Consider now the analogous paradigm that has been developed to test priming effects when the connection between prime and target is episodic or newly formed, so called episodic priming. For example, Howard (1988a, 1988b), Howard, Helsey, and Shaw (1986) and Rabinowitz (1986) asked young and older adults to study word pairs (e.g., card-water) or sentences (e.g., The dragon ate the fudge) and then to recognize words as old or new, presented one at a time. An "episodic priming effect" is said to occur when target recognition is faster following a word from the same pair or sentence (e.g., fudge following dragon), than from a different pair or sentence. Because episodic priming effects require the formation of new connections between word concepts, and because these connections are more difficult for older adults to establish under the commitment learning principle, the NST predicts an age-related deficit for this task.

However, results from episodic priming studies generally show comparable episodic priming effects for young and older adults, but poorer recognition accuracy for older adults. How are these
surprising results to be explained? First, as with semantic priming tasks, older adults typically have longer absolute response times than young adults and this greater interval between the prime and the response to the target could compensate for a slower transmission of episodic priming.

Second, these results are probably a consequence of the methodological requirement of assessing episodic priming only when a target and its preceding prime word have both been correctly recognized. Within the NST, accurate recognition that a target word is "old" depends on the formation of a new connection between the target word and the experimental context. This new connection can be seen in Figure 8, where uncommitted nodes marked $X'$ connect the "was presented" node with the targets dragon and fudge. Episodic priming within the NST depends on the formation of another new connection, this time between the prime and target, in Figure 8, for example, via an uncommitted node X connecting dragon (prime) with fudge (target). It is consistent with the NST that when a target has been studied sufficiently to be correctly recognized as having been presented, that is, to have a committed node ($X'$) connecting it to the experimental context, then the target is likely to have been studied sufficiently to show episodic priming, that is, to have a committed node (X) connecting it to the prime.

However, with brief study time there is some evidence for an age-related deficit in episodic priming. Under such conditions, Howard, Heisey, and Shaw (1986) observed episodic priming with two nouns from the same sentence for young but not older adults. Recognition accuracy for individual words decreased with study time for both age groups but showed no age difference. This suggests that, under these conditions, older adults have greater difficulty forming new connections between words in the sentence (for demonstrating an episodic priming effect) than forming connections between the words and the experimental context (for demonstrating recognition that the word had been presented). Rabinowitz (1986), however, obtained even lower recognition accuracy than Howard et al., with age differences in recognition but not episodic priming. This variation may reflect the subjects' strategies for learning the stimuli, that is, whether they emphasize
more the association between words or the association with the experimental context.

The commitment learning principle is consistent with the pattern of age differences found in Howard's recall and recognition data, namely, age decrements in cued recall and paired recognition without age decrements in episodic priming and single word recognition (Howard, 1988b; Howard, Helsey & Shaw, 1986). Cued
recall (i.e., What noun occurred in the same sentence as the cue?) and paired recognition (i.e., Did both words occur in the same sentence?) each require a new connection between the node linking the first word (e.g., dragon) with the second word (e.g., fudge), and the node for experimental context. This new connection is made through the node marked X" in Figure 8. Thus, cued recall and paired recognition in these studies required commitment of more nodes (X and X") than did single word recognition (X) or episodic priming tasks (X).

Direct versus Indirect Memory Tasks

A currently popular dimension for describing memory tasks is the involvement or non-involvement of conscious recollection. Episodic priming tasks and repetition priming tasks that show effects of prior experience without seeming to require conscious recollection of those experiences have been called indirect memory tasks. Cued recall or recognition tasks that seem to require conscious recollection have been called direct memory tasks. The dissociation between performance on direct versus indirect memory tasks in normal and amnesic subjects has been viewed by some as evidence that separate and fundamentally different memory systems (i.e., explicit and implicit memory, respectively) underlie performance on each type of task (N.J. Cohen, 1984; Tulving, 1985; see Schacter, 1987 for a recent review). Applied to aging research, this theoretical approach has raised the question of whether these hypothesized memory systems exhibit differential aging effects (Chiarello & Hoyer, 1988; Light & Burke, 1988; Mitchell, 1989).

However, a single memory system suffices to explain age differences within the present theoretical approach. Further, our approach extends to a broad range of memory phenomena and is not limited, in principle, to explaining age differences in direct versus indirect memory tasks. Predictions of the commitment learning principle for indirect tasks parallel predictions of the NST for practice effects in general: repetition increases linkage strength of existing connections (i.e., causes engramment learning) and the rate of increase should be unaffected by aging. The larger age
deficits obtained in direct than indirect memory tasks (e.g., Howard, 1988b; Light & Singh, 1987) reflect the greater number of new connections typically required in direct tasks. However, the commitment learning principle predicts age differences for indirect memory tasks insofar as they require new connections. A similar analysis of direct and indirect memory tasks in terms of the degree to which new associations are involved has been suggested in research on amnesia. Shimamura and Squire (1989) have recently demonstrated, for example, that amnesics who showed preserved semantic and repetition priming, were impaired in priming involving new associations. Further, the size of priming effects for new associations was related to the degree of residual direct memory ability (see also Schacter & Graf, 1986b).

Similarly, the commitment learning principle predicts age-related decrements on indirect memory tasks when new learning is involved. Unfortunately, we know of only one study with data relevant to this prediction, Fry and Howard, cited in Howard (1988b). Subjects were required to complete a word stem (e.g., STAA____) with the first word that came to mind after generating sentences using unrelated word pairs (e.g., QUEEN-STAIRS). When the word stem was presented with a word from the original pair, subjects used the target word to complete the stem more often than when a different word preceded. This effect, demonstrating a new connection between the two words, was the same for young and older adults, although older adults had poorer cued recall. However, under more impoverished or time constrained study conditions, the effect was obtained for young but not older adults.

Thus, age deficits have been obtained in both episodic priming tasks and word stem completion tasks requiring new connections, under conditions that reduce learning. The age deficit in direct recall is consistently more pronounced because this task requires more new connections than do indirect tasks. Finally, even young adults show decreased effects of lexical context on word stem completion under study conditions that reduce new learning (e.g., Graf & Schacter, 1985; Schacter & Graf, 1986a).
Summary and General Predictions

To summarize our discussion of commitment learning, we have outlined an explicit mechanism for new connection formation, and have argued that the deficit in transmission of priming that proved useful in explaining other effects of aging is especially likely to impair the occurrence of commitment learning. Engrainment learning resulting from practice or repetition via pre-existing connections involves a different mechanism in the theory, namely changes in linkage strength following activation, and is unaffected by aging. Our analysis of selected memory tasks in terms of the new versus old connections involved explained available results and provided a basis for new predictions. All other factors being equal, the commitment learning principle predicts that varying the number of new connections required in a task will affect the size of age differences independent of distinctions between direct versus indirect memory or general versus specific encoding, or even effortful versus automatic processes, insofar as these distinctions differ from the one between engrainment and commitment learning.

TOTs: AN EXCEPTION TO THE COMMITMENT LEARNING PRINCIPLE?

TOTs occur when a speaker retrieves the meaning of a familiar word, but is unable to retrieve its phonology. Such retrieval failures are of interest to the field of cognitive aging because they increase with age (Burke et al, 1989), and because they provide an important counterexample to the popular view that age-related declines are primarily in the ability to use or remember new information (fluid intelligence) (see, for example, Horn, 1982; Light, 1988). TOTs indicate that even highly familiar information can be more difficult to retrieve with age. However, TOTs do not contradict the commitment learning principle that age deficits increase with the amount of commitment learning required for accurate performance. Rather, both TOTs and the commitment learning principle can be explained as derivatives of the Transmission Deficit hypothesis: TOTs occur when already established
connections for infrequently or non-recently retrieved words become weakened due to age and infrequent or unrecent activation, and transmit reduced priming to phonological nodes. As discussed below, this instantiation of the Transmission Deficit hypothesis provides a detailed explanation of how TOTs originate and are resolved in young and older adults.

The Origin of TOTs Within the NST

TOTs originate under the NST when a lexical node becomes activated, providing access to semantic information about the target word, but at least some of its connected phonological nodes remain unactivated because insufficient priming is transmitted to enable activation, a transmission deficit related to frequency and recency of use. For example, a TOT for velcro would occur if the lexical node velcro(concrete noun) becomes activated but transmits too little priming to enable some of its connected phonological nodes to become activated (see Figure 9).

Frequency and Recency of Use

Why do most TOTs involve words that are rarely and/or not recently used (see Burke et al., 1989)? The reason under the NST is that frequency and recency of activation influence the rate and amount of priming transmitted across a connection and connections to the phonological nodes of rarely and unrecently used words become so weak as to transmit insufficient priming to enable activation. A similar explanation holds for why object naming is faster for high than low frequency names in normal individuals (e.g., Huttenlocher & Kubicek, 1983; Oldfield & Wingfield, 1965) and aphasics (e.g., Tweedy & Schulman, 1982), and for why phonological errors are more common for low than high frequency words, both experimentally induced (e.g., MacKay, 1970) and spontaneously occurring (e.g., Stemberger & MacWhinney, 1986). The lexical node for a high frequency word will have stronger connections to its phonological nodes. These stronger connections will tend to reduce phonological errors, which occur when the correct node has acquired less priming than some other,
inappropriate node in the same phonological domain when the activating mechanism is applied (see Burke et al., 1989).

Resolution of TOTS

TOT words often pop up or come to mind spontaneously, without conscious attempts at retrieval. However, because the weak connections that originally cause TOTs under the NST reflect low production frequency and unrecency, there is no reason to expect these particular connections to recover spontaneously. Rather, an externally delivered boost in priming to the appropriate phonological nodes is required for the target to pop into mind. Consistent with Yaniv and Meyer's (1987) account of incubation effects in both problem solving and language production, Burke et al. (1989) suggest that this boost may arise when the TOT target is no longer in mind and the critical phonological components occur accidentally during internal speech and/or everyday language comprehension. This unconsciously processed internal or external stimulus increases the activation levels of the relevant nodes so that the pop-up can occur.

Persistent Alternates

Persistent alternates refer to words that come repeatedly and involuntarily to mind instead of the target word, even though the subject rejects the persistent alternate as inappropriate. An example from Burke et al. (1989) is dacron, a word that came repeatedly to mind instead of the TOT target, velcro. As in this example, persistent alternates are usually similar to the target word in sound and meaning, and share the same domain or syntactic class as the target. Persistent alternates also increase the time required for the spontaneous resolution of a TOT, even though subjects who report more alternates also tend to recall more information about the target such as its initial phoneme and how many syllables it has (see Burke et al., 1989).

The NST readily explains these characteristics of persistent alternates. By way of illustration, the sample of nodes in Figure 9 shows how the persistent alternate dacron might come initially to
mind instead of the TOT target, velcro. The lexical node for velcro is connected with a set of predicates such as, say, "is made out of nylon" and "is used as a fastener", some of which are shared with other words such as dacron. For some subjects, for example, velcro may share the predicate "is made out of nylon" with the word dacron (see Figure 9). This shared predicate therefore transmits "top-down" priming to the lexical node for dacron when velcro(concrete noun) becomes activated.

Moreover, dacron will receive additional priming "bottom-up" from some of velcro's phonological nodes. Recall that the TOT for velcro occurs because of a transmission deficit: some of its phonological nodes receive too little priming to become activated, whereas others such as the node for the consonant cluster cr do receive sufficient priming and in fact become activated. These activated phonological nodes will transmit strong priming bottom-up to all lexical nodes containing these components, including, for example, dacron(concrete noun).

Top-down and bottom-up priming therefore summates on dacron(concrete noun) which may become activated as the most primed node in the (concrete noun) domain when the activating mechanism for this domain is next applied. This summation-of-priming factor explains why targets and alternates are phonologically and semantically similar and why alternates share the same domain (syntactic class) as the target: activation occurs by lexical domain and repeated attempts to retrieve the TOT target would yield (activate) alternates only in that domain. This summation-of-priming process also predicts that factors tending to increase the priming delivered to alternates, such as augmented strength of connections due to high frequency of use of the alternate, should increase the probability that the alternate will persistently intrude. Finally, subjects who report more persistent alternates also report more information about the target because transmission of priming influences both of these variables: retrieving partial information about a target depends on how much priming is transmitted, and so does retrieving a persistent alternate.
Figure 9. Illustration of the spread of priming preceding retrieval of a persistent alternate (dacron) for the TOT (velcro).

How Age Influences TOTs

Theories of cognitive aging must explain why resolution times increase with age whereas persistent alternates and information available about the TOT target decrease with age (see Burke et al., 1989). All three phenomena are consistent with the Transmission Deficit hypothesis. If aging reduces the priming delivered to nodes...
in the phonological system, phonological information would be less primed, leading to reduced probability of activation and reduced information retrieval about the target, as observed. Older adults would also retrieve fewer alternates (as observed) because bottom-up priming from phonological nodes and top-down priming from shared predicates would both be reduced. Finally, pop-ups would take longer for older adults (as observed) because more external input would be required to raise priming levels to a point where the target nodes could be activated. The Transmission Deficit hypothesis therefore explains how TOTs arise and are resolved in general, and how TOTs change with age.

The Single-source Factor: Some New Predictions

The Transmission Deficit hypothesis makes some clear predictions regarding conditions under which age differences are likely to be most pronounced, all other factors being equal. For example, age differences are likely to be pronounced when a node critical to a task receives priming from only a single source or connection within the network. Age-linked transmission deficits are very likely to affect performance in such a task because no other sources of priming will be able to offset the reduced priming across that critical connection.

The single-source factor and the concept of a critical connection are best illustrated by examining the priming of phonological nodes during attempts to produce a TOT word. In general, higher level phonological nodes have only a single or critical top-down connection and so receive a single source of priming without the possibility of convergence or priming summation. A syllable node, for example, receives top-down priming from a single lexical node during production (see Figure 2). As Burke et al. (1989) point out, this limitation in the number of sources that can deliver priming to phonological nodes during language production may explain why phonological but not semantic information is inaccessible in TOTs: Reverse TOTs where someone can produce or recognize the sequence of sounds for a familiar word but cannot access its lexical node (so as to indicate that the sounds represent a known word) are extremely unlikely in the theory: a lexical node receives too many
sources of priming from phonological and other nodes to suffer a transmission deficit. And as predicted, such reverse TOTs have never been observed or reported.

However, this single-source factor does not apply in the semantic priming paradigm, discussed above, a fact that may help explain why age differences are so small and difficult to obtain using this task. Nor does the single-source factor apply in the case of everyday word perception, where priming converges or sums onto a single lexical node from many phonological nodes (see Figure 2) and perhaps also from nodes in other sensory and conceptual systems. For example, we can activate the node for *dog*(noun) on the basis of convergent priming arriving from the sight, sound, touch, and perhaps even smell of a dog, as well as from the process of imagining any of these characteristics. The many propositions that we have stored about dogs can also contribute convergent priming for activating *dog*(noun) (Jones, 1985).

The single-source factor in production suggests an interesting new prediction: the asymmetry between the maximal rate of production vs. perception seen in young adults (MacKay, 1987) will be accentuated in the case of older adults. That is, young adults can perceive speech at a faster rate than they can produce it, an asymmetry due in part to the single-source factor in production: priming comes from a single source in production (via the divergent or one-to-many top-down connections in action hierarchies), but comes from several convergent sources in perception (via the summating or many-to-one bottom-up connections in perceptual hierarchies).

The maximal rate of perception is determined empirically by presenting speeded or time-compressed speech using electromechanical devices that systematically sample and compress acoustic signals so as to provide a wide range of acceleration without introducing pitch changes. Young adults can perceive connected paragraphs accelerated in this way at rates up to 400 words per minute (about 20 to 30 ms. per phoneme), but their maximal rate of producing speech is much slower (see MacKay, 1987). The prediction under the Transmission Deficit hypothesis is that this asymmetry will be exaggerated in older adults: the ratio of
maximal perception rate to maximal production rate will be greater for older adults than for younger adults.

AGING AND ERROR DETECTION: FURTHER NEW PREDICTIONS

Some of the evidence cited earlier as consistent with the NST connection formation mechanism might also be consistent with other perspectives in the literature, for example, Hebb's distinction between type A versus type B intelligence, and the Cattell-Horn distinction between fluid versus crystalized intelligence (Horn & Cattell, 1966). As Salthouse (1985) points out, "age effects are generally greatest on tasks requiring the acquisition or transformation of information (sometimes referred to as fluid intellectual activities), but are minimal to non-existent on tasks involving the retrieval or utilization of prior knowledge (p.2)". However, the NST specifies how old connections are used, and how and when new connections are acquired, whereas earlier concepts such as the transformation versus the utilization of information have never been clearly specified (see Light, 1987). Moreover, unlike the NST, these earlier formulations concerning new knowledge have difficulty with age-linked deficits involving well-established knowledge, for example, the TOT phenomenon.

Nonetheless, the question arises whether connection formation processes in the NST predict any genuinely new and surprising phenomena that are not closely related to already established empirical phenomena. What follows is an answer to that question: a description of some new and untested predictions that follow logically from the Transmission Deficit hypothesis and the NST account of error detection, discussed below.

The NST Account of Error Detection

Explaining how slips of the tongue are detected requires no new mechanisms, and follows directly from the mechanisms for connection formation and awareness in the NST. As MacKay (1990) points out, three conditions are necessary for awareness under the NST:
1) **The Novelty Condition:** Under the Novelty Condition, two or more nodes that have never been activated in conjunction before must become conjointly activated. For example, the expression 'pertinent novelty' illustrates the novelty condition if the speaker/listener has never encountered this particular combination of adjective and noun before.

2) **The Pertinence Condition:** Under the Pertinence condition, the domains containing the novel nodes must be familiar and sequentially related. For example, the expression 'pertinent novelty' illustrates the pertinence condition if the speaker/listener knows that 'pertinent' is an adjective, that 'novelty' is a noun, and that adjectives followed by nouns make up noun phrases in English.

3) **The Strength-of-Priming Condition:** Under the Strength-of-Priming Condition, the novel and pertinent node(s) activated in error must deliver sufficient priming to an uncommitted node to trigger the binding nodes for prolonged activation (i.e., awareness of the error) and orienting reactions (that halt ongoing production and enable error correction). We argue below that this third condition provides the basis for an age-related impairment in error detection under the Transmission Deficit hypothesis.

Slips of the tongue automatically meet the novelty and pertinence conditions for awareness or detection: Slips always involve the conjoint activation of two or more nodes that have never been conjointly activated before (i.e., novelty) and the domains containing the nodes activated in error are familiar and sequentially related (i.e., pertinent) because errors do not alter the original (intended) syntax or sequential domains of an utterance. That is, as discussed above, errors occur under the NST when a node fails to achieve greatest priming in its domain when the activating mechanism is applied, and some other "extraneous" node in the domain that receives more-priming becomes activated. As a result, when slips occur, verbs interchange with other verbs, adjectives interchange with other adjectives, and nouns interchange with other nouns, as when "a full tank of gas" is misproduced as, "a full
gas of tank". However, words from different domains or syntactic categories almost never interchange in speech errors. For example, adjectives almost never interchange with nouns, as in the hypothetical error, "a full tank of gas" misproduced as "a gas tank of full". This same generalization also holds for phonological domains and is known as the sequential class regularity (MacKay, 1979; Fromkin, 1973; A. Cohen, 1967). As already noted, these mechanisms underlying the sequential class regularity also underlie the syntactic similarity phenomenon observed when persistent alternates substitute for TOT targets (see above).

However, novelty and pertinence are not sufficient for awareness, and speech errors often pass unnoticed because they fail to meet the third condition for awareness. That is, nodes activated in error often deliver insufficient priming to an uncommitted node to trigger the binding nodes for prolonged activation and awareness. In the case of young adults, the reason for the insufficient priming is that a large number of connections sometimes intervenes between a unit activated in error and the novel unit (uncommitted node) that it primes. Consider for example the three Spoonerisms or phonological transposition errors (from Motley, Baars, & Camden, 1983) in Table 3. When crawl space is misproduced as crawl srace, an uncommitted or novel phonological unit representing syllable-initial sr becomes strongly primed because there exists no committed node representing syllable-initial sr in English. The priming on this uncommitted node is strong because no other nodes intervene between the nodes activated in error (the nodes representing the consonants /s/ and /r/) and the uncommitted node. As a result, young adults are very likely to detect this error. Turning to the second example where dump seat is misproduced as sump deat, an uncommitted or novel lexical node becomes primed because there exists no committed node representing the word deat in English. However, the priming on this uncommitted node will be weak because a committed node representing the syllable deat intervenes between the nodes activated in error (the nodes representing the consonants /s/ and /d/) and the uncommitted node at the lexical level, so that young adults are less likely to detect this error. Turning to the third example, where tool carts is misproduced as
Table 3

The Probability of Detection Predicted Under the NST for Three Spoonerisms or Phonological Transposition Errors.

<table>
<thead>
<tr>
<th>Intended</th>
<th>Error</th>
<th>Distance</th>
<th>Predicted Probability of Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>crawl space</td>
<td>crawl scrace</td>
<td>0</td>
<td>high</td>
</tr>
<tr>
<td>dump seat</td>
<td>sump deat</td>
<td>2</td>
<td>moderate</td>
</tr>
<tr>
<td>tool carts</td>
<td>cool tarts</td>
<td>4.5*</td>
<td>low</td>
</tr>
</tbody>
</table>

Note: Distance represents the number of connections intervening between a node activated in error and the first uncommitted node that it conjointly primes. The arrow stands for "was misproduced as". The asterisk indicates an ambiguity with respect to level (see text for explanation).

cool tarts in the sentence, "They were moving tool carts down the assembly line", an uncommitted or novel proposition node becomes primed because the speaker is unlikely to have a committed node representing the proposition, "They were moving cool tarts down the assembly line." Thus, the priming on this uncommitted node will be extremely weak because about four other committed nodes intervene between the nodes activated in error (again the nodes representing /s/ and /d/) and the uncommitted node at the proposition level, so that this error is very likely to pass undetected. As noted in Table 3, however, the level of the uncommitted node is ambiguous in this example: if the speaker lacks a committed node for the phrase, cool tarts, then commitment of a novel phrase node rather than a novel propositional node is called for.
The New Prediction: Age and the Detection of Speech Errors

From the Strength-of-Priming condition and the examples above it is clear that probability of error detection is directly related to strength of priming. This means that a deficit in the transmission of priming will reduce the probability of error detection. This means that, all other factors being equal, errors will be detected with higher probability in young than in older adults under the Transmission Deficit hypothesis.

CONCLUSIONS

Although we have applied the NST and the Transmission Deficit hypothesis to only a few cognitive aging phenomena in the present paper, the theory cuts across paradigm-specific boundaries and seems applicable to a wide range of tasks, some of which are new or relatively unexplored within the field of cognitive aging, for example, time-compressed speech perception. Moreover, we have only spelled out some of the predictions that follow from the theory; there are others. For example, the NST predicts that effects of ambiguity on errors induced by delayed auditory feedback (see MacKay, in press) should decline with age, and so should "perception without awareness" or subliminal perception effects (see MacKay, 1990) and the verbal transformation effect (see MacKay, 1987). At this stage, however, testing or even spelling out all of these novel predictions may not be as important as addressing some of the other goals underlying development of a theory: to organize and integrate the existing literature in the research traditions of the field, and to establish priorities for future research within those traditions (see Salthouse, 1988).

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