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Errors, Ambiguity, and Awareness in Language Perception and Production

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Three interrelated puzzles have been haunting my work on speech errors, almost since it began in 1965. The awareness puzzle is one, and it consists of two parts. Part 1 of the awareness puzzle concerns relations between awareness and the "adjustments" or accommodations that often follow the production of errors. For example, the speaker who *misproduced* "cow tracks" as "track cow*z*" (Garrett, 1980; see also MacKay, 1979) selected the appropriate context-dependent plural *unconsciously* from among the three alternatives that English allows (/z/, /ez/, and /s/) for the transposed word *track*. The unconscious nature of these "context-sensitive accommodations" indicates that speakers can choose unconsciously among alternative outputs, contrary to the proposal of Reason (1984) and others that unconscious processes are inflexible and that only conscious processes are sensitive to context and capable of choice. Context-sensitive accommodations also undermine Marcel's proposal (1983) that choice among actions can serve as a criterion for consciousness. The puzzle is how these unconscious choices are made.

The awareness puzzle, Part 2, is how unconscious perceptual factors give rise to production errors. In particular, how do unconsciously processed ambig-

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uities cause speech errors in sentence completion tasks (as in MacKay, 1966, 1969, 1970) where a subject is presented with a sentence fragment, thinks up a relevant completion, and produces the entire sentence aloud as quickly as possible? After a series of, say, 100 recorded sentence completions, the experimenter asks the subject if any of the sentence fragments seemed unusual or ambiguous and then goes over each sentence with the subject, reading aloud the subject's completion and asking the subject whether his or her completion seems grammatical and relevant to the fragment. The experimenter then informs the subject that some of the fragments were ambiguous (e.g., "Having a ball with his case, Perry Mason . . ."), and that others were unambiguous (e.g., "Having a pencil with his case, Perry Mason . . ."). (Unambiguous versions were formed by changing a single word in an otherwise identical ambiguous sentence, and a counterbalanced design ensured that no one subject received both versions of the same sentence.) The experimenter next announces the two meanings for each ambiguous fragment and asks the subjects whether they had seen both of these meanings while thinking up the completion, and if not, which meaning they saw. By these measures, subjects almost invariably fail to notice any of the ambiguities: they report awareness of only one meaning and claim to be unaware of the other meaning when completing the ambiguous fragments.

However, significantly more ambiguous than unambiguous fragments evoked speech errors, and the nature of these errors indicates that the unseen meaning had an unconscious or subliminal effect on how the subjects completed the sentences. For example, one subject produced the sentence, "After stopping arguing in the court [fragment], Wimbleton was perjured, I mean, disqualified" but reported being unaware of the meaning "court of law," despite its obvious connection with the error, *perjured*. Deepening the puzzle, whole classes of errors such as stuttering (segment repetition) that bore no direct relation to the unseen meanings also occurred more frequently for ambiguous than for unambiguous fragments. The awareness puzzle, Part 2, is how the unseen meanings of ambiguous sentences can trigger speech errors, both directly and indirectly.

Puzzle 2, the practice puzzle, is why no simple relation exists between prior practice and the probability of speech errors at various levels. Prior practice (repetition over the course of a lifetime during everyday speech) reduced the probability of errors and is confounded with the level of a unit in the speech production system (see MacKay, 1982): during everyday speech, phoneme units receive more practice than syllable units, which receive more practice than word units, which receive more practice than phrase units. Logically, then, errors and level in the hierarchy should be highly correlated: errors involving phonemes should be least likely, and errors involving phrases should be most likely. However, no such pattern is observed. Phrases participate in fewer errors than do words, and syllables participate in fewer errors than do phonemes (see Garnham, Shillcock, Brown, Mill, & Cutler, 1982). Why are naturally occurring errors distributed in this way with respect to level and prior practice? The suggestion of Dell (1986) and Shattuck-Hufnagel (1983) that phrases and syllables do not exist as speech production units augments rather than resolves Puzzle 2; after all, the fact that syllables and phrases *sometimes* participate in errors must surely be explained in terms of production units.

Puzzle 3, the error detectability puzzle, also comes in two parts. Part 1 is why the level or focus of awareness shifts following self-produced phonetic and phonological errors. As adults, we are normally aware of the higher level aspects of a conversation, but not of the phonemes or phonetics of pronunciation, in either self-produced or other-produced speech. However, a self-produced phonetic error such as a slurred speech sound will immediately bring our awareness down to the phonetic level. The error detectability puzzle, Part 1, is how such errors shift the level of awareness to the phonetic level.

The error detectability puzzle, Part 2, concerns a difference in the detectability of self-produced and other-produced errors. *Self-produced* word substitutions are detected and corrected with fairly high frequency (60%), as in "Moses, I mean, Noah built the ark." However, otherwise similar [illegible] *produced by others* are detected with relatively low probability: even [illegible] warned of possible errors, subjects under no time pressure whatsoever rarely detect other-produced "errors," as in "How many animals of each kind did Moses bring on the ark?" (Eriksen & Mattson, 1981). This is the error detectability puzzle, Part 2: If self-produced and other-produced speech are represented via the same system (a reasonable assumption; see MacKay, 1987, pp. 14–140), why are self-produced errors easier to detect than other-produced errors?

Organization of the Chapter

The main point of the present chapter is that these and other related puzzles are no longer [illegible]. They follow logically from a recently developed theory of language perception and production (MacKay, 1987, 1988). I originally developed the theory[1] not just to explain speech errors or even language production, but to address much more general issues: the mechanisms underlying sequencing and timing in behavior, the effects of practice on behavior, the speed–accuracy trade-off in the perception and production of skilled behavior, asymmetries in the ability to perceive as opposed to produce skilled behavior, the perception of ambiguous inputs, the use of perceptual feedback in monitoring skilled behavior, and the effects of delayed and amplified auditory feedback on the production of speech and other cognitive skills. However, the theory also ended up making numerous claims about errors, including error-correction errors, bumper-car errors, haplologies, dysgraphia, omission errors in speech and typing, internally generated errors, tongue twisters, stuttering, perceptually based production errors, experimentally induced per-

[1]The reader is referred to MacKay (1987) for a more extensive discussion of the original theory, its supporting data, and its relations to other theories, such as that of McClelland, Rumelhart, and the PDP Research Group (1986).

ceptual errors, and relations between slips of the tongue and slips of the ear.

In what follows, I briefly summarize this theory and then extend it so as to explain consciousness and its relation to error perception and production. As soon as is feasible in developing the theory, I show its bearing on the puzzles discussed above.

Basics of the Node Structure Theory

Nodes, the basic components of the theory, fall into three classes, depending on the nature of their connections with one another: muscle movement nodes, sensory analysis nodes, and mental nodes. Sensory analysis nodes represent patterns of input, registering, say, speech inputs via the basilar membrane and associated auditory pathways, for example. Muscle movement nodes represent patterns of muscle movement for the respiratory, laryngeal, velar, and articulatory organs, among others. Mental nodes represent neither sensory experience nor patterns of muscle movement, but higher level cognitive components common to both perception and production. Mental nodes for speech include phonological nodes representing segments and syllables and sentential nodes representing words and phrases. These shared perception–production units send "top-down" outputs to muscle movement nodes for use during production and receive "bottom-up" inputs from sensory analysis nodes for use during perception (including the perception of self-generated feedback), and they send symmetrical top-down and bottom-up signals among each other. Mental nodes become active during perception, production, and cognition, as when we perceive a sentence and produce it, either aloud, or within the imagination (internal speech).

Nodes represent not just intersections in a descriptive parsing tree (as in, say, Anderson, 1983), but theoretical processing units (as in, say, Wickelgren, 1979). All nodes respond in the same way to basic variables such as practice (repeated activation) and share a set of relatively simple and universal processing characteristics: activation, priming, self-inhibition, linkage strength, and satiation.

The Distinction between Activation and Priming

The distinction between activation and priming is fundamental to the node structure theory, but it derives from the original use of these terms by Lashley (1951), rather than from current uses of the same terms. Node activation is an all-or-none process that is self-sustained, like neural activation; it lasts for a specifiable period of time, regardless of whether the sources that led originally to activation continue to provide input. Unlike neural activation, however, node activation can—and, in the case of mental or perception–production nodes, usually does—involve more than one neuron. Neurons and nodes also differ greatly in how long they remain activated and in how long they take

to recover from activation: isolated neurons require only a few milliseconds to recover from activation, whereas nodes can take over a hundred milliseconds to recover (see MacKay, 1987, pp. 141–157).

Node activation also differs from the concept of spreading activation in propositional network theories such as Anderson's (1983). Node activation never "spreads," and its intensity never changes; unlike spreading activation, node activation remains constant with "distance," fatigue, and the number of other nodes connected to an activated node. Also unlike spreading activation, node activation is terminated by a brief period of reduced excitability known

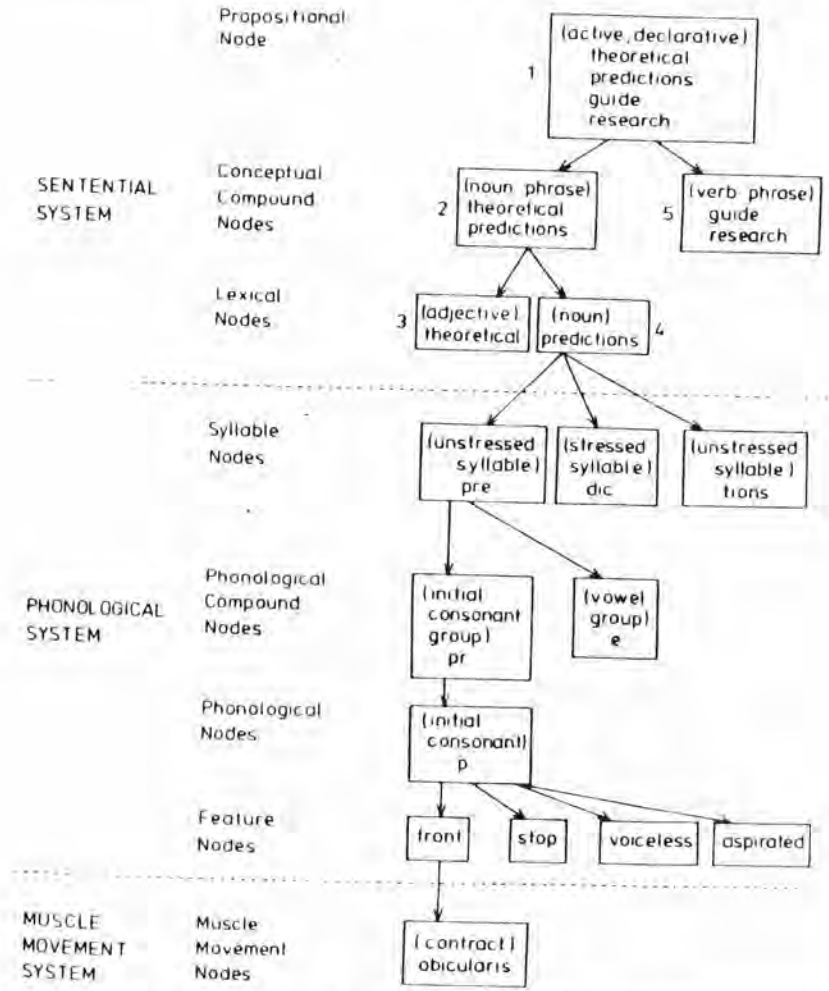

Figure 1. A top-down hierarchy of nodes for producing aspects of the sentence "Theoretical predictions guide research." The numbers represent the order in which the nodes become activated during production (from MacKay, 1987).

as *self-inhibition* (discussed below). Finally, node activation is sequential and nonautomatic in nature; a special activating mechanism (sequence node) must become engaged to determine when and in what order different nodes will become activated. By way of illustration, the numbers in Figure 1 represent the typical order in which the nodes for a sentence become activated during production.

During the period of self-inhibition following activation, the level of priming of a node falls below normal or resting level (see Figure 2). Then follows the recovery cycle, during which priming first rises above and then returns to resting level (see Figure 2). The mechanism underlying self-inhibition is an inhibitory collateral, or "satellite," that connects with and receives a connection from its "parent" node. The inhibitory satellite has a very high but otherwise standard threshold and becomes activated only after a set amount of input from its activated parent. Once activated, the satellite inhibits and deactivates its parent, thereby deactivating itself and enabling recovery to begin. This self-inhibition mechanism helps explain a variety of empirical

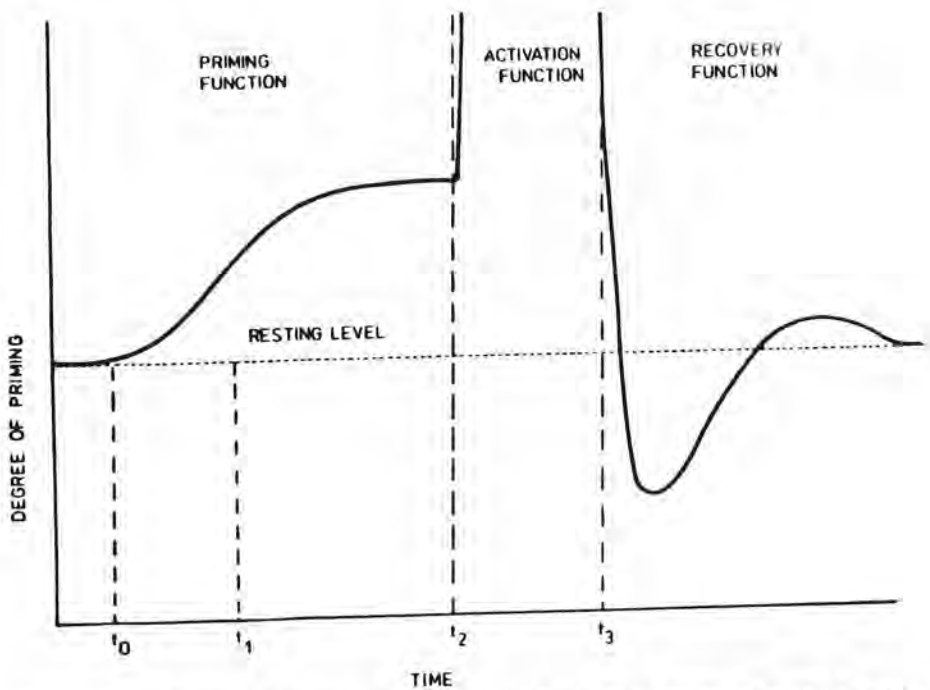

FIGURE 2. The priming, activation, and recovery phases for a single node. The priming function shows how priming summates to asymptote following the onset of priming at $t0$. The activation function illustrates the multiplication of priming and self-sustained activation until time $t3$. The recovery cycle that follows the termination of activation shows how priming first falls below resting level (self-inhibition), rebounds (the hyperexcitability phase), and then returns to resting level.

phenomena, for example, pathological stuttering and the effects of delayed and amplified auditory feedback (see MacKay, 1987, pp. 178–193). This chapter argues that self-inhibition also plays a central role in awareness and error detection.

Priming refers to a transmission across an active connection that, in some respects resembles the automatic spread of activation in other theories such as those of Dell (1986) and McClelland, Rumelhart, and the PDP Research Group (1986). However, priming is necessary to prepare a connected node for possible activation *as defined above:* In order to become *activated,* nodes must receive priming during the period of self-sustained activation of a directly or indirectly connected node. An activated node primes its connected nodes most strongly (first-order priming), and an unactivated node receiving first-order priming primes its connected nodes less strongly (second-order priming), and so on, up to n^{th}-order priming, where n is currently unknown (see below), and $n + 1^{th}$-order priming does not alter the resting state.

Priming summates both spatially (across two or more simultaneously active connections to the same node) and temporally (during the time that any given connection remains active). However, summation of priming cannot by itself cause a connected node to become activated: priming accumulates only to some subthreshold asymptotic level (see Figure 2). Moreover, priming does not self-sustain but gradually decays as soon as input into its connected nodes stops. Also unlike activation, priming is not followed by a period of self-inhibition and recovery and is order-free or parallel in nature; an active source primes its connected nodes simultaneously, and no special triggering mechanism is required to determine when and in what order the nodes become primed.

Activation Hierarchies. The structure of connections between nodes can be described as hierarchic with respect to activation and heterarchic with respect to priming (see MacKay, 1987, p. 23). Figure 1 illustrates aspects of an activation hierarchy, specifically, the hierarchy of top-down connections between nodes for producing the sentence "Theoretical predictions guide research." Following MacKay (1982), I designate each node by a two-component label: the content that the node represents appears in italics, followed by its sequential domain (explained below) in parentheses. Thus, the highest level node representing the entire thought underlying this particular sentence has the *content "Theoretical predictions guide research,"* occurs in the domain (active declarative), and is labeled *theoretical predictions guide research*(active declarative). Activating this particular node primes two phrase nodes top-down: *theoretical predictions*(noun phrase) and *guide research*(verb phrase) (see Figure 1). Activating *theoretical predictions*(noun phrase) primes two lexical nodes, *theoretical*(adjective) and *predictions*(noun). These lexical nodes prime specific phonological nodes, representing syllables (e.g., *pre*), phonological compounds (e.g., *pr*), segments (e.g., *p*), and features (e.g., the one representing the frontal place of articulation of *p*). The reader is referred to

MacKay (1972, 1973, 1978, 1979, 1987) and Treiman (1983) for evidence supporting the particular units and connections illustrated in Figure 1, which omits the more complex but otherwise similar hierarchy of nodes underlying the control of muscle movements.

Linkage Strength

Linkage strength is a relatively long-term characteristic of connections that determines how rapidly they can transmit priming per unit of time. The initial slope of a priming function is sensitive to differences in linkage strength (see MacKay, 1982): highly practiced connections have a steep slope, whereas unpracticed connections have a shallower slope. Linkage strength also influences how much priming a connection can transmit before hitting asymptote. Connections with high linkage strength transmit priming more rapidly and up to a higher asymptote than do connections with low linkage strength.

Practice (the frequency with which a node has been primed or activated via a particular connection in the past) increases linkage strength, an effect known as *engrainment learning* (MacKay, 1988, after James, 1890) that helps explain a wide range of practice effects in the psychological literature.

Satiation

Satiation refers to a process in which nodes become less responsive to priming as a result of continuously repeated activation over a prolonged period of time. Like activation, self-inhibition, priming, and engrainment learning, satiation is an extremely simple process if taken by itself, as in the above discussion. However, each of these processes interacts with the others in complex ways that depend on the current state of the node and on its history of activity over the course of a lifetime. Satiation varies with the extent and duration of repeated activation and manifests itself in reduced rebound and prolonged self-inhibition following activation. Activating a node increases the linkage strength of its connections and causes its connected nodes to become primed. Linkage strength influences how much and how rapidly priming can be transmitted across a connection. Finally, priming is necessary for activation and influences the probability of activating a node in error (see MacKay, 1982). As discussed below, the *mechanisms* likely to underlie these basic processes are also quite complex.

Sequence Nodes: The Activating Mechanism for Content Nodes

The nodes in the preceding discussion are known as *content nodes* because they represent the form or content of action, perception, and thought. A different type of nodes, known as *sequence nodes*, constitute the nonspecific activating mechanisms that activate content nodes according to a "most-primed-wins principle." As discussed below, sequence nodes also organize content nodes into domains and determine the serial order in which content nodes become activated.

Domains

Sequence nodes are connected to and activate not individual content nodes, but categories or domains of content nodes, where a domain consists of a set of nodes that share the same sequential properties (see MacKay, 1987, pp. 50–55). I use capital letters to denote sequence nodes and parentheses to denote the corresponding domain of content nodes. For example, content nodes in the domain (vowel) all share the same sequential properties or privileges of occurrence in the syllables of English or any other language and are activated by the sequence node VOWEL. Nodes in the domain (color adjective) likewise all share the same sequential properties or privileges of occurrence in English and are activated by the sequence node COLOR ADJECTIVE.

Multiplication of Priming

When activated, a sequence node multiples the priming of every node connected with it by some large factor within a relatively brief period of time. This multiplicative process has no effect on unprimed nodes, but it soon serves to activate (i.e., bring to threshold) the content node with the greatest degree of priming in its domain. For example, COLOR ADJECTIVE is connected to and, when activated, multiplies the priming of the dozens of content nodes in the domain (color adjective).

The Most-Primed-Wins Principle

The "most-primed-wins" activation principle follows directly from the nature of the connections between sequence and content nodes. Once a sequence node becomes activated, it automatically and simultaneously multiplies the priming of the entire domain of content nodes connected with it, increasing their level of priming rapidly over time. Normally, however, one node in a domain has more priming than all the others, and this "most-primed" node reaches threshold first and becomes activated.

During production, content nodes generally achieve their most-primed status via priming "from above." In producing the adjective *green*, for example, a superordinate node such as *green apples*(noun phrase) becomes activated and strongly primes *green*(color adjective) (see Figure 3). Being most primed when its activation mechanism begins multiplying its priming, this primed-

from-above node reaches threshold sooner than other "extraneous" nodes in its domain and becomes activated.

Content nodes can achieve their most-primed status "from below" as well as "from above." For example, visual perception of the color green or the printed word *green* will prime *green*(color adjective) from below. *Green*(color adjective) then passes second-order priming to its connected sequence node (see Figure 3), enabling COLOR ADJECTIVE to become activated, and in turn activating the most primed content node in its domain, that is, *green*(color adjective) itself. This most-primed-wins principle is the basis for all node activation (see MacKay, 1987, pp. 49–55).

Quenching

The term *quenching* refers to a threshold mechanism that, if exceeded, causes content nodes to inhibit rather than prime their sequence nodes. This process enables an activated content node to quickly quench, or deactivate, its corresponding sequence node. Quenching is necessary to prevent reverbatory reactivation via the return connection between an activated content node and its sequence node (see Figure 3) and to ensure that only one content node becomes activated at any one time: without being quenched, a sequence node could potentially activate every node in its domain, causing behavior to break down.

Timing Nodes: The Activation Mechanism for Sequence Nodes

Timing nodes control the rate of perception and production by determining how rapidly sequence nodes become activated. They connect with and activate sequence nodes in the same way that sequence nodes connect with and activate content nodes, so that sequence nodes within a system (e.g., the phonological system and the sentential system; see Figure 1) can be considered a domain of nodes sharing the same sequential function. Timing nodes "self-activate" according to an endogenous rhythm, and timing nodes for different systems exhibit different endogenous rhythms. Each activation of a timing node multiplies the priming of connected sequence nodes and activates the most primed one, following the most-primed-wins principle, just as for content nodes.

How Sequence Nodes Code Sequential Rules

Connections between sequence nodes represent sequential rules that resolve the sequencing conflict that occurs when two or more sequence nodes have received simultaneous priming. The sequence nodes COLOR ADJECTIVE and NOUN, for example, are connected in such a way as to represent the

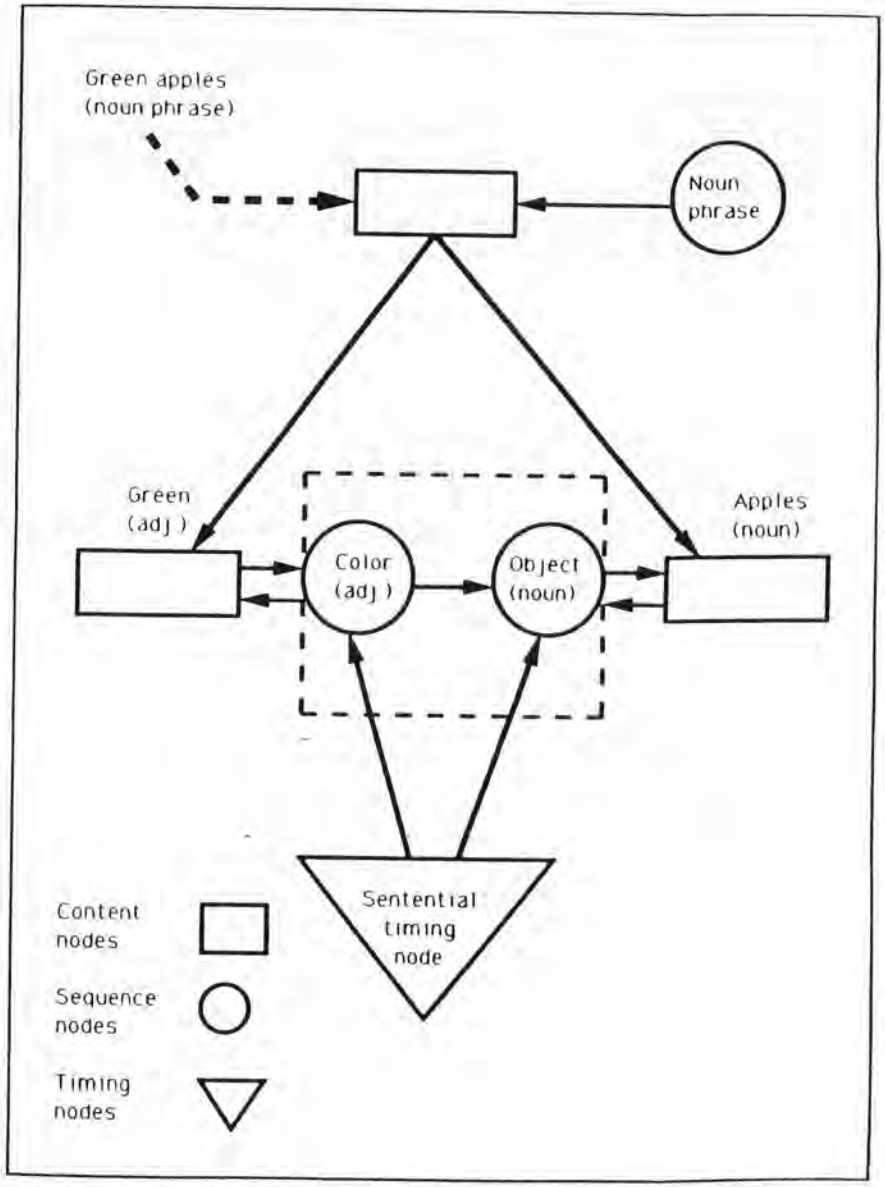

FIGURE 3. The order of top-down processes (in brackets) underlying the activation of the content nodes (in circles) and the sentential timing node for producing the noun phrase *green apples*.

rule that color adjectives precede nouns in English noun phrases.[2] Similarly, the sequence nodes INITIAL CONSONANT GROUP and VOWEL GROUP are connected in such a way as to represent the rule that initial consonants in a syllable precede the vowel and the final consonants.

Inhibitory connections determine the order relation among sequence nodes: Whenever two or more sequentially organized sequence nodes receive simultaneous priming, the sequence node that must be activated first inhibits its connected sequence nodes, so that it can become activated first under the most-primed-wins principle. Quenching this first sequence node releases the other sequence nodes from inhibition, and the most primed of these becomes activated next, and so on. For example, when COLOR ADJECTIVE and NOUN receive simultaneous priming from noun phrase constituents, COLOR ADJECTIVE inhibits NOUN, dominates in degree of priming, and becomes activated. However, once COLOR ADJECTIVE is quenched, NOUN is released from inhibition, dominates in degree of priming, and becomes activated. This process thus determines the sequence for this and any other noun phrase consisting of a color adjective and a noun.[3]

Speech Errors under the Node Structure Theory

As discussed in MacKay (1982, 1983, 1985, 1987), activation via the most-primed-wins principle serves a variety of important functions but is susceptible to error. Specifically, substitution errors occur when an "intended" or primed-from-above node fails to achieve the greatest priming in its domain when the most-primed-wins activating mechanism is applied, and some other "extraneous" node receiving more priming becomes activated. This explains why the substituted and substituting components in these errors almost invariably belong to the same sequential class (the sequential class regularity; see MacKay, 1979, 1987). At the sentential level, nouns substitute for other nouns, verbs for verbs, and not for, say, nouns or adjectives; at the morphological level, prefixes substitute for other prefixes, suffixes for other suffixes, and never prefixes for suffixes; at the syllabic level, initial consonant clusters substitute for other initial clusters, final for final, but never initial for final; and at the segment level, vowels substitute for vowels, consonants for consonants, and never vowels for consonants. Substitution errors result from a most-primed-wins competition between priming of content nodes, rather than from competition between activating mechanisms (because the same activating mechanism activates both the correct and the incorrect nodes), or from competition between plans (which correspond to a preformed hierarchy such as the one in Figure 1; see MacKay, 1982). The sequential class regularity should also hold statistically for other errors, including paradigmatic errors such as blends (see MacKay, 1972, 1973), because an activating mechanism (sequence node) can activate and misactivate nodes only within the same sequential domain as the appropriate or intended-to-be-activated node, but the theory also predicts exceptions to the sequential class regularity under special circumstances exhibiting regularities of their own (see MacKay, 1987, pp. 60–61).

The automatic integration of top-down and bottom-up priming can also give rise to blends, phonologically similar word substitutions, and "Freudian" errors, including Freudian slips of the ear (see Dell, 1980; MacKay, 1973, 1987). Indeed, errors in general are largely attributable to the automatic manner in which mental nodes integrate priming from heterogeneous sources. However, mental nodes also make the relatively infrequent errors that do occur especially easy to detect and correct (see below).

The Level-within-a-System Effect

As noted in the introduction, phrase nodes participate in fewer errors than do lexical nodes, and syllable nodes participate in fewer errors than do segment nodes. This frequency distribution can be explained in terms of speed–accuracy trade-off: lover level nodes are activated at a faster rate than higher level nodes in the same system, so that the probability of error is reduced for higher level units. That is, nodes at lower levels in a hierarchy are more numerous and become activated at a faster rate than higher level nodes. For example, segments are produced much faster than syllables: a syllable node is activate every, say, 400 milliseconds on the average, whereas a segment node is activated every, say, 150 milliseconds on the average. This faster rate allows less time for the priming on lower level nodes to summate and thereby increases the probability that the wrong node will become activated under the most-primed-wins principle (see MacKay, 1982, 1987). However, this speed–accuracy trade-off effect will be confined *within a system:* lower level units will exhibit greater errors than higher level units only *within the same system*

[2]Rules such as (color adjective + noun) are of course needed for producing adjectives in preferred sequences such as *fast red car*. However, it remains to be determined whether specific rules such as (color adjective + noun) can be "inherited" from a more general rule such as (adjective + noun), so that a color adjective content node connects with and is potentially activated by both ADJECTIVE and COLOR ADJECTIVE.

[3]Sequential rules such as (color adjective + noun) bear a surface resemblance to the phrase structure rules of Chomsky (1957) and Gazdar (1981) such as Noun Phrase → Adjective + Noun, where the arrow stands for "is rewritten as." Like phrase structure rules, sequential rules are nontransformational and refer to categories of units—in this example, the set of all adjectives and all nouns. There are many differences, however. For example, there is no sense in which the sequence node NOUN PHRASE is "rewritten" as COLOR ADJECTIVE + NOUN in the node structure theory (see also MacKay, 1974). Rather, the lexical content nodes connected to some particular noun phrase node simultaneously prime their respective sequence nodes, which happen to be NOUN and COLOR ADJECTIVE. The node structure theory also postulates new rules and new sequential domains, such as (initial consonant group + vowel group), which were unforeseen in phrase structure grammars. See MacKay (1987, p. 51) for other differences in the detailed nature of phrase structure categories and sequential domains).

because the timing nodes that determine activation rate emit faster pulse rates for lower level systems than for higher level systems (see above; MacKay, 1987).

The *discontinuity* in the distribution of naturally occurring speech errors across systems is attributable to practice and "connectivity" under the node structure theory. That is, word errors occur more frequently than syllable errors (see Garnham *et al.*, 1982) because lexical nodes have less prior practice than syllable nodes, and because lexical nodes enjoy greater connectivity: they are directly connected to a large number of sensory and conceptual systems that phonological nodes are not directly connected to (see MacKay, 1987, p. 38). These systems contribute additional sources of extraneous priming to lexical nodes, so that word errors are more likely than phonological errors.

Ambiguity and Speech Errors

Effects of ambiguity on speech errors fall into two classes: direct effects and indirect effects. I argue below that these effects of ambiguity are attributable to three mechanisms that serve many other functions within the node structure theory: mental or perception–production nodes, the priming–activation relationship, and the most-primed-wins activation principle. These same three mechanisms are also required for explaining experimentally induced "Freudian" slips (see Motley & Baars, 1979) and the more general class of word substitutions that Meringer (1908) called "situational intrusions," which are attributable to priming arising from contextual factors within an ongoing conversational situation: objects just noticed, words just read or heard, the nature of the relationship between the speaker and the listener, and things recently thought of or weighing on one's mind.

Direct Top-Down Effects of Ambiguity on Speech Errors

Significantly more ambiguous than unambiguous fragments in MacKay (1966, 1969) prompted irrelevant (tangential) completions or evoked ungrammatical completions, spoonerisms, and word substitutions, and priming from the unseen meaning was directly responsible for these effects. Tangential completions were defined as ones that the subject agreed during the post-experimental interview had no logical connection with the original fragment. Example tangential completions are "Knowing that visiting relatives can be bothersome, I was confused" and "Knowing how little jockeys drove cars, I mumbled." Ungrammatical completions were defined as ones where the subject agreed during the postexperimental interview that the sentence would not be acceptable as grammatical English. Examples are "Knowing the minister's hope of marrying Anna was impractical, he *disbanded* the idea" and "Although the officers were convincing men, the *message* they gave *were* not." Other

errors included spoonerisms, for example, "Having a ball with his case, Merry Pason, I mean Perry Mason . . ." and word substitutions such as "After stopping arguing in the court, Wimbleton was perjured, I mean, disqualified." The unseen meaning in this last example must have primed extraneous nodes, including *perjured* (past participle), which became activated in error under the most-primed-wins principle when the (past participle) activating mechanism was applied.

Misreadings—as in "Although the idea of Hitler was awful" misread as "Although that idea of Hitler's was awful"—were attributable to ambiguity, but not directly. In this and all other misreadings of ambiguous fragments, the misreading disambiguated the fragment by eliminating the meaning that the subject claimed not to have seen when thinking up the completion. Here the conscious representation of the sentence overrode the primary stimulus for reading, that is bottom-up priming from the sentence itself.

Errors that Ambiguity Does Not Cause. I conclude this section with a note on errors that ambiguity does *not* cause (see also MacKay, 1987, p. 119): Ambiguity does not cause garden path errors in production resembling the garden path errors that occur in comprehension, where a listener perceives the wrong meaning of an ambiguous word—such as, say, *crane*—and mistakes the topic of conversation to be *bird cranes* rather than *machine cranes*. Production errors resembling garden path miscomprehensions have never been reported: Normal speakers never begin to discuss, say, *machine cranes* and then *inadvertently* end up discussing *bird cranes*.

Indirect Top-Down Effects of Ambiguity on Speech Errors

MacKay (1966) found that stuttering (segment repetition) occurred more frequently in ambiguous than in unambiguous fragments, and MacKay (1969) used an error induction technique to demonstrate that this finding must reflect an indirect rather than a direct effect of ambiguity on phonological errors. The phonological errors were induced experimentally by means of delayed and amplified auditory feedback (DAAF). When hearing DAAF from their own voice with a 0.2-second delay, speakers reliably generate large numbers of phonetic and phonological errors, including transpositions, prolongations, omissions, slurs, substitutions, and repetitions, or stutters (Fairbanks & Guttman, 1958).

As in MacKay (1966), the subjects in MacKay (1969) thought up a relevant completion for a sentence fragment but then produced their completed sentence aloud as quickly as possible *under DAAF*. The dependent variable was probability of repetition errors, and ambiguous sentences elicited significantly more repetitions than did ambiguous sentences, both wile the subject was reading the fragments and while the subject was producing the completions.

(Structural complexity and possible speed–accuracy trade-offs were controlled across ambiguous versus unambiguous sentences.)

These findings indicate that ambiguity at sentential levels can indirectly influence repetition errors involving phonological units, and this indirect top-down effect is readily explained under the node structure assumption that phonological nodes for perceiving and producing speech are identical. During perception, the unseen meaning of the ambiguous fragments automatically primes extraneous lexical nodes, which in turn prime extraneous phonological nodes, and during production, this extraneous top-down priming combines with extraneous bottom-up priming from the DAAF arriving at a just-activated phonological node (see MacKay, 1987, pp. 178–190). Ambiguity therefore increases repetition errors by increasing the likelihood that just-activated phonological nodes receive the greatest priming in their domain and become reactivated in error under the most-primed-wins principle.

As an interesting footnote, MacKay (1969) replicated all of the above findings *without DAAF* by having pathological stutterers complete the same sentence fragments in a separate experiment. However, recent theoretical analyses suggest that it is important to distinguish between "intrinsic" and "feedback-induced" stutterers (see MacKay, 1987, pp. 192–193) in future versions of this replication experiment. MacKay (1987, pp. 160–161) presented convincing evidence that "intrinsic stuttering" originates within the muscle movement system (unlike "feedback-induced" stuttering, which originates within the phonological system), and if both intrinsic and feedback-induced stutterers can be shown to exhibit an effect of ambiguity during sentence completion, then priming must spread to a much greater extent than MacKay (1987, p. 10) assumed, that is, all the way from sentential nodes representing the ambiguities to muscle movement nodes, where intrinsic stuttering originates.

As another interesting footnote, the basic mechanisms discussed above (priming, most-primed-wins activation, and mental or perception–production nodes) may also underlie errors that are induced experimentally via anticipatory bias techniques (where a cue signals that the subject must produce a pair of "target words," but unbeknownst to the subjects, the preceding word pairs have primed the spoonerized version of these words; see Baars, Motley, & MacKay, 1975); via word-order competition techniques (where a cue signals that the subjects must produce a pair of visually presented words in reverse order; see Baars & Motley, 1976); via phrase-order competition techniques (where a cue signals that the subjects must produce a pair of visually presented phrases in reverse order; see Baars, 1980); and via "tongue twister" or rapid iteration techniques (see, e.g., MacKay, 1971; as MacKay, 1982, pointed out, the term *tongue twister technique* is a misnomer: these techniques induce phonological errors rather than "neuromotor" errors, as Motley, Baars, & Camden, 1983, assumed).

Other Indirect Top-Down Effects on Speech Errors. MacKay and Bowman (1969) reported another indirect top-down effect of semantics on speech errors induced experimentally by means of DAAF. The top-down effect resulted from practice at the sentential/semantic level: The subjects (highly proficient German–English bilinguals) practiced producing a sentence 12 times, each time at maximal rate with normal feedback, and then put on a pair of earphones and produced another, "transfer," sentence in their other language as rapidly as possible with a 0.2-second delay in DAAF. The transfer sentence had either an identical meaning to or a completely different meaning from the sentence practiced. For example, if the originally practiced sentence was "The wanderlust seized him as it once had his grandfather," then "Die Wanderlust packte ihn wie einst seinen Grossvater" is a transfer sentence with virtually identical meaning but, of course, radically different phonology from the original.

The results were dramatic: Significantly fewer DAAF errors were observed for transfer sentences with identical meaning than for those with different meaning. This finding indicates that practice at the sentential level (in one language) influences the probability of phonological errors (in the other language). Under the assumption that nodes representing the same sentential concepts are identical whatever the language, practice increased the linkage strength of sentential system nodes for producing the transfer sentences and thereby increased the transmission of priming to appropriate lower level phonological nodes, so as to reduce the probability of DAAF errors (see MacKay, 1982).

Ambiguity in General

Ambiguity is often defined as an *input* phenomenon (ambiguous stimulus patterns are open to two or more distinct interpretations), but this "surface definition" has always raised problems because ambiguous stimuli are not necessarily *psychologically* ambiguous (see MacKay, 1966, 1970). However, node structure mechanisms underlying the processing of ambiguity enable a *theoretical* definition that is much more general in nature and seems immune to this problem: Ambiguity occurs in the theory whenever two or more nodes in the same domain simultaneously receive comparable levels of priming (MacKay, 1987, pp. 138–139). Under this definition, ambiguity is a ubiquitous issue, applying to any node in any system, and represents the major cause of errors in all input and output domains. Indeed, MacKay (1987) viewed ambiguity as one of the main reasons for the evolution of the most-primed-wins principle and mental or perception–production nodes. Baars (1983, 1985) also saw the need for a "deep" or theoretical definition of ambiguity as a "choice point." However, output choice points in Baars (1985) correspond to different ways of saying something, another problematic "surface definition."

Node Commitment and Decommitment

Let us return now to the development of the node structure theory. The term *node commitment* refers to an extremely general process in which new or never previously activated nodes become activated. As we will see, node commitment is triggered automatically by "pertinent novelty," requires neither intention nor volition, provides the basis for consciousness, and explains the awareness puzzle.

Uncommitted Connections and the Commitment Threshold

Uncommitted connections are prestructured connections with such weak linkage strength that they pass on too little priming to enable a connected node to become activated when its triggering mechanism is applied. Nodes receiving nothing but uncommitted connections are uncommitted nodes, and all mental nodes begin this way. Each connects initially to thousands of other nodes, and during the lifetime of an individual, only a small fraction of these prestructured connections becomes committed or capable of transmitting enough priming to permit activation of the connected node. Node commitment therefore enables a select few out of an excess of weak but prestructured connections to become functional.

Commitment Threshold. The term *commitment threshold* refers to the minimum level of priming that a node must receive in order to become activated; below this minimum level, even multiplication by an activating mechanism cannot boost priming to the activation threshold. For example, let us say that a sequence node self-sustains its activation for a set period of 20 milliseconds and multiplies the priming of its connected nodes by a factor of 1.2 every millisecond. If the original degree of priming of the most primed content node in the domain exceeds commitment level, this multiplication factor suffices to cause activation within 20 milliseconds or less. However, if the original priming of the most primed content node falls below commitment level, the multiplied priming remains subthreshold, so that activation cannot occur. Note that many nodes are likely to have multiplied priming values that fall between resting level and commitment threshold (see Figure 4), so that sequence nodes have no way of directly activating a specific uncommitted node.

The Commitment Mechanism: Binding Nodes

Binding nodes provide a booster input that enables the extremely weak connections to an uncommitted node to become strong enough to transmit commitment levels of priming, so that the uncommitted node is transformed into a committed node that consistently codes a specific cognitive content. Like

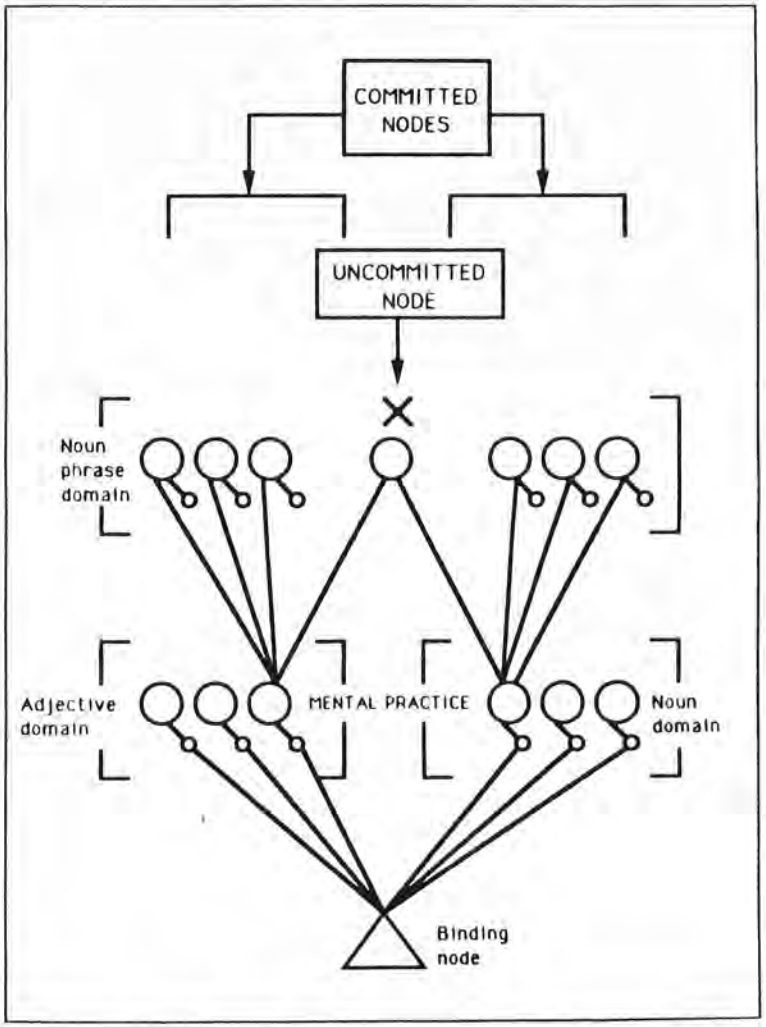

Figure 4. The noun phrase binding node (triangle) commits the uncommitted node *mental practice*(noun phrase), by inhibiting the inhibitory satellites (small circles) of parent nodes (larger circles) in the (adjective) and (noun) domains.

sequence nodes, binding nodes connect with a large number of content nodes, usually in two or more sequential domains, but unlike sequence nodes, binding nodes are relatively few in number, are *inhibitory* in nature, and act on the self-inhibition mechanism of content nodes. That is, binding nodes connect with the self-inhibitory "satellite," and not with the "parent" node itself, so that when a binding node becomes activated, it prevents self-inhibition in all the content nodes to which it is connected. This means that currently activated

nodes will remain activated for a prolonged period of time because their self-inhibitory mechanism now fails to shut them off. In this way, a binding node transmits nonspecific input simultaneously to two or more domains of content nodes but alters the activity pattern only of specific "target nodes" (those nodes undergoing activation at the time) and selectively enhances convergent priming to a single uncommitted node that can then become activated under the most-primed-wins principle. If binding nodes directly boosted the activity of specific target nodes rather than indirectly inhibiting the self-inhibition mechanisms of many unspecified nodes, too many binding nodes would be needed, that is, as many binding nodes as there are pairs of content nodes.

Activating an uncommitted content node in this way increases the linkage strength of its bottom-up connections, thereby improving the asymptotic level and rate of priming via those connections. The commitment of top-down connections follows almost immediately, without further engagement or reactivation of the binding nodes. Specifically, once an uncommitted node becomes activated, it transmits first-order priming to all of its connected nodes, including the two lower level nodes that are still undergoing prolonged activation. Because a connection transmitting first-order priming to activated nodes constitutes the basic condition for a major increase in linkage strength, top-down connections become strengthened soon after their newly committed node becomes activated. With further activations, linkage strength increases further, until bottom-up and top-down priming exceeds commitment threshold. At this point, the connections have become committed so that activation can proceed automatically without calling for booster input from binding nodes.

Decommitment

A newly committed node with recently strengthened bottom-up and top-down connections represents a specific cognitive content, but relatively weakly. Minor increases in linkage strength resulting from one or even several activations of an uncommitted node are relatively fragile and can decay over a period of, say, hours. As a result, unless newly committed nodes undergo repeated activation, their connections can become decommitted or revert to uncommitted status. To permanently commit a node for a particular pertinent novelty, repeated engagement of a binding node may sometimes be necessary. By contrast, highly practiced nodes have relatively unfragile linkage strength that endures for many years.

Pertinent Novelty and Orienting Reactions

The term *pertinent novelty* refers to a coincidence of node activations (internally or externally triggered) that has never occurred in simultaneous combination before but calls up an established sequence node. For example, the phrase *pertinent novelty* constitutes an instance of pertinent novelty if the hearer "knows" that *pertinent* is an adjective, that *novelty* is a noun, and that an adjective followed by a noun constitutes a noun phrase, but he or she has never experienced this particular combination of adjective and noun before; that is, there exists no node committed to the content *pertinent novelty*(noun phrase).

When pertinent novelty occurs, the pertinent sequence node (NOUN PHRASE in the example above) will be activated but will fail to activate any of the nodes in its domain and will therefore fail to quench. It is this "failure to quench" that signals pertinent novelty and triggers the binding nodes: like content nodes, binding nodes receive input from a sequence node but have a much higher threshold and become activated only following prolonged input from a sequence node that has failed to quench. That is, novel inputs will activate a pertinent sequence node whose failure to quench will activate its connected binding node. As a result, the process of node commitment runs off automatically if the timing nodes for a system have been engaged.

Orienting Reactions: Side Effects of Pertinent Novelty

Besides calling up binding nodes, pertinent novelty triggers orienting reactions that include emotional components (e.g., surprise); autonomic components (e.g., increased skin conductance, cardiac deceleration, and pupil dilation); and behavioral components (e.g., inhibition of ongoing activity) (Neumann, 1987). As discussed below, instances of pertinent novelty such as speech errors often trigger these orienting reactions, but because errors often pass undetected (see below), they cannot be operationally identified with orienting reactions or other measures of surprise, contrary to Baars (1985). Note also that, unlike other theories (e.g., Baars, 1988), the node structure theory generates orienting responses without complicated mismatch mechanisms for comparing representations of an intention with representations of the resulting error.

Examples of Pertinent Novelty and Bottom-Up Binding

I will illustrate the bottom-up binding process first abstractly, and then concretely. Pertinent novelty occurs when an uncommitted node, X, receives conjoint first-order priming from two or more lower level nodes, A, B, . . . , and calls up its sequence node. Because A and B, . . . , normally become self-inhibited soon after activation, spatiotemporal summation of priming from A and B, . . . , fails to reach X's commitment level without outside help. The outside help comes when X's sequence node fails to quench and activates its binding node: The binding node inhibits the relevant self-inhibitory satellites, causing prolonged activation of A and B, . . . , which increases the time available for temporal summation at uncommitted node X and enables X to reach commitment threshold and become activated.

As a more concrete illustration of how binding nodes work, consider the child who knows the concepts *mental* and *practice* but encounters for the first time a pertinent novelty, the expression *mental practice*. That is, there exist the two already-committed parent nodes with inhibitory satellites shown in Figure 4: *mental*(adjective) and *practice*(noun). *Mental*(adjective) is connected to several nodes in the (noun phrase) domain, including committed nodes such as *mental arithmetic*(noun phrase) and uncommitted nodes such as *X* in Figure 4. The other committed node, *practice*(noun), is also connected to uncommitted node *X* as well as to perhaps several hundred other nodes, including, say, the committed node *basketball practice*(noun phrase).

Now, only uncommitted node *X* receives convergent (spatially and temporally summating) priming during the normal period that *mental*(adjective) and *practice*(noun) remain activated, but this convergent priming is too weak to enable activation of *X* when its triggering mechanism (NOUN PHRASE) is called up and applied. This constitutes an instance of pertinent novelty: NOUN PHRASE will continue its activation unquenched, causing activation of its binding node, NOUN PHRASE (underlined capitals denote binding nodes and square brackets denote the corresponding domain *of the binding node*, so that the domain of NOUN PHRASE is [noun phrase]). NOUN PHRASE now inhibits the self-inhibitory mechanisms for [noun phrase], the domain of inhibitory satellites for all potential noun phrase constituents, including (adjective) and (noun). Consequently, [noun phrase] nodes that are currently undergoing activation—namely, *mental*(adjective) and *practice*(noun)—fail to self-inhibit and so engage in prolonged activation. The resulting temporal and spatial summation provides uncommitted node *X* with the required boost up to commitment levels of priming, enabling NOUN PHRASE to activate *X*. Activation of *X*, in turn, increases the linkage strength of bottom-up connections to *X*, and enables *X* eventually to code the content *mental practice*(noun phrase) without engaging the binding node for introducing prolonged first-order bottom-up priming.

Consciousness, Node Commitment, and Creativity

The prolonged activation of content nodes that occurs during node commitment corresponds to consciousness under the node structure theory: we become conscious of a concept during the time when the node representing that concept is undergoing prolonged activation. This explains why we normally become conscious of what is new, rather than of what is old or highly familiar; neither priming nor self-inhibited activation of old or automatically activated connections is *per se* sufficient for consciousness: the self-inhibitory process normally shuts off activation after a set period and prevents awareness. It also explains why stimuli that are repeated or presented for prolonged periods drop out of awareness, as in habituation: repeated activation of a node results in satiation, which reduces the degree of priming and the probability of both activation and prolonged activation.

Awareness, Practice, and Level in the Hierarchy

As noted in discussing the practice puzzle, we normally become aware of the higher level aspects of a conversation, but not of the phonetics or phonology of pronunciation. Under the node structure theory, this correlation between consciousness and level of processing is related to the linkage strength of units in the hierarchy: consciousness is usually limited to higher level concepts because pertinent novelty triggers consciousness, and what is novel in sentences is generally not phonemes but higher level concepts (see also Sokolov, 1963). However, linkage strength and level in the hierarchy are not perfectly correlated. For example, adults occasionally learn new words, which approach automaticity at the phonological and lexical levels only after considerable practice. Moreover, concepts at levels much higher than the word can also achieve automaticity, given sufficient practice. Even very high level (suprasentential) patterns of thought sometimes become so practiced as to be triggered unconsciously (see, e.g., MacKay & Konishi, 1980). Although consciousness *usually* begins at the lexical level, the many clear exceptions to this pattern are readily explained in the theory.

Awareness and Creativity in Language Production

Creativity requires the formation of new connections under the node structure theory, and connection formation invariably gives rise to awareness. However, the awareness puzzle, Part 1, provides what seems to be an exception: the context-sensitive adjustments for about-to-occur speech errors illustrate preprogrammed creativity that does not give rise to awareness. Speakers are unaware of choosing a new but appropriate plural ending after making an error such as *track cowz* instead of *cow tracks;* the original intention to pluralize may be conscious, but not the choice of the appropriate plural, /z/ rather than /s/, when the last segment of the error word is voiced rather than unvoiced. Paradoxical lack of awareness also occurs when speakers produce rule-governed aspects of never-previously-encountered words, for example, adding appropriate plural or verb agreement endings or aspirating unvoiced stops (/p, t, or k/) in word-initial but not in noninitial positions (see MacKay, 1982, for other examples).

Preprogrammed creativity is unconscious under the node structure theory because there exist highly practiced programs for introducing context-sensitive changes without forming new connections at the phonological or phonetic levels (see MacKay, 1982). For example, the program for pluralization consists of a content node in the sentential system that represents the concept *regular plural* and transmits priming to a phonological "archiphoneme" node that nonspecifically represents both *s* and *z*, transmitting priming to all of the feature nodes for /s/ and /z/ except those for voicing (i.e., + voice and − voice). Now, activating a word-final segment node that is *voiced*, as in *cow*, will automatically prime /z/ bottom up, and being most primed in its domain, /z/

will become activated, causing production of *cowz*. However, activating a word-final segment node that is unvoiced, as in *track*, will automatically prime /s/ bottom up, and being most primed, /s/ will become activated, giving *tracks*. As a result, producing regular plurals or any other highly practiced context-sensitive accommodation requires neither awareness nor the formation of new connections.

Pertinent Novelty and Error Detection

Error detection illustrates a special case of the relation between novelty, awareness, and node commitment in the node structure theory. Note first that errors invariably result in the production of units that are novel *at some level*. For example, *dump seat* misproduced as *sump deat* involves novel lexical units because *sump* and *deat* are nonwords in English. Similarly, *crawl space* misproduced as *crawl srace* involves novel phonological units because syllable-initial *sr* does not occur in English; *Fly the plane and buy the boat* misproduced as *Fly the boat and buy the plane* involves a novel propositional unit because boats do not fly. Similarly, *tool carts* misproduced as *cool tarts* in the intended sentence *They were moving tool carts down the assembly line* involves a novel propositional unit if the speaker lacks a committed node for *They were moving cool tarts down the assembly line*(proposition) (examples from Motley *et al.*, 1983).

Note also that the nodes activated in novel combination in speech errors invariably fall into familiar classes or domains, so that speech errors represent instances of pertinent novelty that can potentially trigger orienting reactions for signaling the occurrence of the error. However, different errors differ in how many connections separate the units produced in error from the new or uncommitted node that they prime, and this "distance" plays a critical role in error detection. Compare the effects of this distance for two phonological transposition errors (above): *crawl srace* instead of *crawl space*, and *cool tarts* instead of *tool carts* in the intended sentence *They were moving tool carts down the assembly line*. In *crawl space*, no committed node represents *sr*(initial consonant group) for speakers of English, so that when *s*(initial stop) and *r*(initial liquid) are activated in error, first-order bottom-up convergent priming is transmitted immediately (distance 0) to an uncommitted phonological node, thereby triggering binding nodes and orienting reactions, causing output to terminate), and *awareness* (prolonged activation) that enables error detection. Indeed, this rapid detection sequence may explain why phonologically novel errors are so rare in overt speech (see Fromkin, 1971): These errors can be detected so rapidly that speakers can stop speaking and prevent their occurrence before they appear in the surface output (see Levelt, 1984; MacKay, 1988).

However, the theory predicts that error detection will be both less efficient and less likely when many intervening connections separate the uncommitted node from the phonological units produced in error. In the *cool tarts* error, for example, nodes higher in the hierarchy already exist for representing the

segments *c*(initial consonant group) and *t*(initial consonant group), the syllables *cool*(stressed syllable) and *tarts*(stressed syllable), and the words *cool*(adjective) and *tarts*(noun). Even *cool tarts*(noun phrase) is likely to exist as an already-committed node, so that the possibility of orienting reactions and error detection at that level is precluded. However, the proposition node *They were moving cool tarts down the assembly line*(proposition) almost certainly does not exist as an already-committed node, so that activating *cool tarts*(noun phrase) in the context *move down the assembly line* could potentially trigger orienting reactions and awareness of the error. However, *cool tarts*(noun phrase) is unlikely to achieve greatest priming in its domain and become activated while the subject is producing the remainder of this sentence because of the number of connections separating *cool tarts*(noun phrase) from its source of first-order priming at the phonological level, so that such an error is likely to pass undetected. More generally, the node structure theory predicts that the probability of error detection will vary with the proximity of the units produced in error to the uncommitted node that they jointly prime. This proximity factor may also contribute to the fact that speakers fail to correct about 40% of all word substitution errors.

It is important to note that *correct* output cannot trigger a similar process for indicating that the output is, in fact, correct. Appropriate or intended-to-be-activated nodes transmit convergent priming to existing higher level nodes that have just been activated and have quenched their activating mechanism, and that therefore cannot trigger surprise, awareness, and detection that the output is, in fact, error-free (which may explain why determining that a response is correct is so difficult; see MacKay, 1987, p. 166). It is also important to note that other-produced errors cannot be detected in the same way as self-produced errors under the node structure theory. For a self-produced error (as in "How many animals of each kind did Moses, I mean, Noah bring on the ark?"), orienting reactions indicating that an error has taken place can be triggered soon after the activation of the wrong node, *Moses*(proper noun). However, there is no similar basis at this level for a listener to detect an *other-produced* error: listeners will be engaged in node commitment regardless of whether the input is correct ("How many animals of each kind did Noah bring on the ark?") or incorrect ("How many animals of each kind did Moses bring on the ark?"). (The reader is referred to MacKay, 1987, p. 166, for a detailed discussion of other differences between detecting self-produced and detecting other-produced errors, e.g., the fact that detecting other-produced errors depends on the size or level of the units involved, whereas detecting self-produced errors does not.)

Error Detection and the Flexibility of Awareness

As already noted, adults *normally* become aware only of higher level concepts (words and above) and *normally* remain unaware of the phonemes making up the words and phrases. However, speech errors can automatically trigger shifts in the level of awareness. Even subphonemic errors such as the

slurring of a speech sound can enter consciousness, so that the speaker becomes aware of what sound was slurred, and perhaps even of the higher level (pragmatic) implications of the slur, for example, possible drunkenness and the inadvisability of driving a car (see MacKay, 1988). The reason is that even phonetic errors constitute pertinent novelty that can engage the mechanism for consciousness and connection formation for nodes currently undergoing activation at any level in the system. However, these lower level errors will enter awareness only when lower level systems are being activated, as must invariably occur during self-produced speech, but not necessarily during perception of other-produced speech (see MacKay, 1987, pp. 62–89).

Other Theories of Error Detection

The editor in editor theories (such as e.g., Baars *et al.*, 1975) is a mechanism that "listens to" self-produced internal or external feedback, compares this feedback with the intended output, identifies errors, and then computes corrections by using a duplicate copy of the information originally available to the motor system. As MacKay (1987, pp. 167–168) pointed out, editor theories encounter difficulties in explaining why errors occur at all, why errors sometimes pass unnoticed, why detecting correct responses takes more time than detecting incorrect responses (Rabbitt, Vyas, & Fearnley, 1972), and why detecting self-produced errors differs from detecting other-produced errors, or, more generally, how error detection relates to detection at large. MacKay (1973), Motley, Camden, and Baars (1982) and Motley *et al.* (1983) discussed additional difficulties facing editor theories. The node structure theory avoids all of these difficulties and can also account for the data that have been gathered in support of editor theories. The node structure theory also avoids the pitfalls of the "formulation hypothesis," until recently the main alternative to editor theories (see Motley, Baars, & Camden, 1983). Under the formulation hypothesis, "unacceptable" errors almost never get formulated, because the full range of units for expressing them does not exist. For example, nonword errors such as *bart doard* instead of *dart board* are rare because there are no lexical units representing *bart* and *doard*. As Motley *et al.* (1983) pointed out, the formulation hypothesis fails to explain why errors that are unacceptable at the pragmatic level (e.g, *cool tits* instead of *tool kits*) are so rare in studies of experimentally induced speech errors, why correct responses to these targets exhibit long latencies and increased skin conductance, and why increased skin conductance also accompanies near-miss errors of this sort (e.g., *cool kits* as well as *cool tits*). None of these phenomena present problems for the node structure theory.

Ambiguity and Awareness

As MacKay (1988) pointed out, a tripartite distinction between priming, activation, and prolonged activation is needed to account for conscious and unconscious processing in language perception and production. This same tripartite distinction is also required to explain the automatic resolution of ambiguity, sequential awareness in the perception of sentential ambiguity, and semantic blending in the completion of ambiguous sentences.

Automatic Resolution of Ambiguity

The most-primed-wins principle resolves ambiguities on the basis of priming from any type of contextual source (including states of mind; Baars, 1988), and the fact that priming spreads rapidly and in parallel enables large amounts of heterogeneous information arriving either before or after an ambiguous word to quickly resolve ambiguities within 700 milliseconds (Swinney, 1979) or less (MacKay, 1970). Even without context, the most-primed-wins principle disambiguates words on the basis of conceptual frequency (linkage strength) (see MacKay, 1987, p. 135). Finally, the most-primed-wins mechanism explains why we almost invariably resolve ambiguity in an either-or way: we initially comprehend only one meaning of an ambiguous word or sentence (MacKay, 1966, 1970) because only the node receiving the greatest priming in a domain can become activated at any one time.

Sequential Awareness of Ambiguous Alternatives

Whereas both interpretations of ambiguous sentences are primed rapidly, unconsciously, and in parallel, prolonged activation and awareness of the two alternatives is slow and sequential under the node structure theory. When a subject is processing a lexically ambiguous sentence, both of its alternative readings receive unconscious processing (priming) at the same time, but only one alternative meaning at a time becomes conscious. When subjects are instructed to become aware of *both* meanings, as in MacKay and Bever (1967), awareness is sequential: they perceive one meaning after the other. Moreover, the second meaning is perceived relatively slowly: the MacKay and Bever (1967) subjects took a remarkably long time to become aware of both meanings of lexically ambiguous sentences (about 7.5 seconds on the average). The reason is that a nonautomatic process is required to boost the priming of nodes representing the second meaning so that these primed but not activated nodes can become activated under the most-primed-wins principle when the activating mechanism is applied again. More generally, the fact that consciousness requires prolonged activation in the node structure theory predicts that all conscious processing will be relatively slow.

Semantic Blending

The term *semantic blending* refers to an effect of unseen meanings on the completions of ambiguous fragments reported in MacKay (1966, 1969). Ex-

amples are *Discussing the problems with the mathematicians in Germany, Oppenheimer grew red in the face* (where the speaker interpreted the fragment to mean "mathematical problems" but not "mathematician problems") and *Claiming the work was done over on the roof, he asked them to do it again* (where the speaker claimed awareness of the meaning "the work was completed over there" but not "the work was redone"). Again, the unseen meaning must have contributed priming that helped determine which nodes for generating the completion received the most priming and became activated under the most-primed-wins principle. A similar semantic blending process may underlie the "atmosphere effects" reported in Motley and Baars (1979) and Motley, Camden, and Baars (1983).

Conclusions

Relations between priming, activation, and prolonged activation in the node structure theory provide a solution to the awareness puzzle: Priming and activation are unconscious, and contextual sources of priming enable preformed programs to become activated, so as to automatically introduce context-sensitive adjustments to an about-to-occur error. However, contextual sources of priming also represent the basic cause of errors, and by introducing such a contextual source of priming, ambiguity causes errors during sentence completion: nodes for both meanings of an ambiguity automatically become primed, even though only one becomes activated and triggers awareness, and priming from nodes representing the unseen meaning directly causes errors such as *After stopping arguing in the court, Wimbleton was perjured, I mean, disqualified,* and indirectly contributes to errors under DAAF.

Explaining the error detectability puzzle is only slightly more complicated: Awareness occurs at lower-than-normal levels following speech errors because errors constitute instances of pertinent novelty that can trigger the mechanisms for prolonged activation (consciousness) and connection formation at any level. However, other-produced errors are detected less often than self-produced errors because lower level errors can trigger prolonged activation (awareness) only when lover level systems are being activated, which invariably occurs when one is *producing* speech, but not necessarily when one is perceiving other-produced speech.

Finally, the node structure theory suggests some interesting reasons for the complexity of the practice puzzle. Four interacting factors in the theory contribute to the complex distribution of naturally occurring speech errors across different levels in an output hierarchy: (1) the fact that phonological nodes tend to have greater prior practice than lexical nodes (so that lexical nodes are more prone to error) but (2) are activated at a faster rate than lexical nodes, thereby becoming *more* prone to error (speed–accuracy trade-off across systems), (3) the fact that lexical nodes have greater connectivity or sources of extraneous priming (which tend to increase the probability of word errors relative to phonological errors); and (4) the fact that lower level nodes in a system are activated at faster rates than higher level nodes *within the same system*, so that they become more prone to error (speed–accuracy trade-off within a system).

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