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Awareness and Error Detection: New Theories and Research Paradigms

DONALD G. MACKAY

Psychology Department, University of California, Los Angeles, California 90024

This paper examines the relation between errors and awareness in two recent theories of error detection in speech: Perceptual Loop theory and Node Structure theory. New data and predictions are discussed, together with some nonobvious limitations of these theories. New paradigms for studying speech error detection are also discussed, together with implications for current theories of the large body of work on error detection in related skills such as reading, typing, and handwriting. © 1992 Academic Press, Inc.

Awareness is a central concept for theories of error detection, which must explain why speakers detect some of their errors, but not others. Moreover, theories of awareness must account for a readily observed relation between errors and awareness: Some aspects of speech processing that normally do not enter awareness do so following a self-produced error. For example, speakers do not become aware of the duration of fricatives such as /sh/ during normal, error-free speech production, but do so when they make a phonetic error, producing , e.g., a slurred or longer-than-normal /sh/, and may even become aware of higher level (pragmatic) implications of such errors, say, inadvisability of driving a car (see MacKay, 1990). This special relation between errors and awareness is nontrivial: Detection and correction of errors could in principle occur without awareness, but as Levelt (1989, p. 21) points out, "self-corrections are hardly ever made without a touch of awareness." Explaining this special relation between errors and awareness presents a clear challenge for theories of awareness and error detection alike.

The present paper takes a first step toward addressing this challenge by examining the relation between errors and awareness in two recently proposed theories of error detection: Levelt's (1989, pp. 469–71) Perceptual Loop theory and MacKay's (1987, 1990) Node Structure theory. New data and predictions are discussed, together with the relevance of these theories to the sizeable body of work on error detection in related cognitive skills such as reading, writing, and typing. Also discussed are some nonobvious limitations of these theories and some new directions for future research.

PERCEPTUAL LOOP THEORY OF ERROR DETECTION

Levelt's (1989) Perceptual Loop Theory (PLT) is a new type of editor theory. In early editor theories, e.g., Baars, Motley, and MacKay (1975), a special pur-

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pose error detector located within the *production system* "listened to" self-produced internal or external feedback, compared this feedback with the intended output so as to identify errors, and then computed corrections using a duplicate copy of the information available to the motor system for producing the original output. Problems with these early editor theories have been discussed elsewhere, e.g., MacKay (1973), Motley, Barrs, and Camden (1983), Berg (1986), and MacKay (1987, pp. 167–168). For example, the editor in theories such as those of Laver (1980) and Motley et al. (1983) seems unparsimonious, duplicating within the production system capabilities of perception at large. However, this problem does not arise in PLT because error detection processes are part of perception at large: the same mechanisms that perceive the speech of others also perceive errors in self-produced speech.

Specifically, systems for perceiving vs producing speech in PLT are separate but interconnected at two specific points in the language production hierarchy. That is, language production proceeds top down through a hierarchy of semantic, phonological, and phonetic units in PLT, but two pathways or "loops" connect phonetic production units to phonetic perception units for perceiving phonetics. One is an "internal loop" that enables perception of one's own inner speech by directly linking phonetic production units to phonetic perception units. The other, "external loop," is essential for perceiving overtly produced, acoustic speech and, although longer and more complex than the internal loop, ends up at the same place as inner speech, namely phonetic perception units. This external loop includes the muscle movement system, airborne and bone-conducted acoustics, and the acoustic perceptual system, which completes the loop by feeding its acoustic analyses to the standard systems for perceiving phonetics, phonology, syntax, and semantics. These standard perceptual systems monitor both internally and externally generated outputs for errors by detecting deviations from linguistic rules or standards.

One attractive feature of PLT is its ability to account for the speed with which many errors are detected. That is, outputs such as "bl . . . (onset of the word black), I mean white" (Levelt, 1984), indicate that some errors can be detected and corrected even before they have been fully articulated. Such rapid error detection is possible within PLT because perceptual processes can proceed so much faster than production processes (see MacKay, 1987, p. 114): Using the internal loop, the system for perceiving words can detect that *black* is in error before its full phonology becomes translated into overt movements of the articulators.

Empirical Support for PLT

A critical source of support for PLT comes from a study of experimentally induced speech errors by Lackner and Tuller (1979). Lackner and Tuller had subjects repeat experimentally constructed tongue twisters such as pi-di-ti-gi at a controlled rate for 30 s, pushing a button as soon as they noticed making an error. This measure of error detection was examined under two experimental conditions: masking vs nonmasking. Subjects in the masking condition produced the tongue twisters while hearing 100-db white noise that masked their auditory feedback, while those in the nonmasking condition produced the same tongue twisters without masking noise.

Results were separately analyzed for substitution errors involving two types of distinctive features: place of articulation errors (e.g., ti-di-ti-gi instead of pi-di-ti-gi) and voicing errors (e.g., bi-di-ti-gi instead of pi-di-ti-gi). Subjects detected place of articulation errors slightly more often in nonmasking than in masking conditions (94% vs 84%), but detected voicing errors much more often in nonmasking conditions than in masking conditions (72% vs 19%). However, detection times for both types of error were shorter in masking conditions than in nonmasking conditions.

To explain this pattern of results, Levelt (1989, pp. 472–473) suggested that masking suppresses use of the external (auditory) loop, so that error monitoring must be accomplished via the internal loop (i.e., the link from the phonetic production system to the phonetic perceptual system). To explain why this effect of masking is specific to voicing errors, Levelt argued that voicing (unlike place of articulation) depends on a small production difference that translates into large acoustic effects. Levelt then argued that the large acoustic effects in voicing errors are easiest to pick up using the external loop (acoustic analysis system), and because this external loop happens to be suppressed in the masking condition, detecting voicing errors becomes relatively more difficult with masking. Finally, the shorter error detection times in masking conditions than in nonmasking conditions reflects the greater length of the overt speech loop relative to the internal speech loop within PLT.

Lackner and Tuller (1979) also compared the time required for subjects to detect their own errors in the production task (above) with the time required for another group of subjects to detect otherwise similar errors in a tape recording of the nonsense syllable strings. Self-produced errors were detected over 100 ms faster than other-produced errors recorded on tape, as if the shorter internal loop could sometimes be used to speed up detection of self-produced errors.

Limitations of PLT

One limitation of PLT concerns the Lackner and Tuller data. Levelt's (1989) arguments from these data seem tenuous on several counts: Consider first the assumption that voicing (unlike place of articulation) depends on a small production difference that translates into large acoustic effects. Contrary to this assumption, there are as many production differences between voiced vs unvoiced speech sounds as there are perceptual differences (Lisker, 1978). Moreover, comparing the "size" of articulatory vs acoustic differences for different phonological features or for different values of the same phonological feature is problematic: To make sense, the comparison requires a theory of the relation between articulatory and acoustic features, and if such a theory were available, the notion of articulatory vs acoustic "size" would almost certainly be irrelevant. By analogy, a comparison of eggs with chickens requires a theory of the relation between the two, and the notion of size is clearly irrelevant to such a theory.

Important aspects of Lackner and Tuller's (1979) data also remain unaddressed in PLT. For example, voicing errors were not only detected less often than place of articulation errors in Lackner and Tuller's nonmasking condition, they also occurred much more often than place of articulation errors (427 vs 214 overall), especially in the masking condition (252 vs 116). Addressing this second aspect of Lackner and Tuller's data is essential because it suggests a possible artifact, namely speed–accuracy trade-off. Thus, errors in general may have been detected faster with masking in Lackner and Tuller not because of reliance on an internal loop, but because of a reduced criterion for accuracy: That is, the masking condition may have induced a lowered criterion that had production effects (more errors) and perceptual effects (more hasty error detection responses and reduced error detection).

The above point touches on a central limitation of PLT: Despite its importance, PLT is relatively undeveloped. Like other editing theories, PLT leaves many relevant questions unanswered. For example, if masking suppresses use of the external (auditory) loop, how is it that in general, speakers automatically adjust the loudness of their output and maintain it at a higher level when masking noise is introduced or increased in loudness during speech (e.g., Siegel & Pick, 1974)? If masking causes suppression of the external loop for error detection, how do speakers monitor and respond to loudness of the masking itself? Other unanswered questions in PLT are how the perceptual system is able to detect deviations from linguistic standards, and how the perceptual system detects the many errors that do not violate linguistic rules, e.g., "appropriateness errors" such as "blue, I mean, light blue" (Levelt, 1984), and word substitutions such as "Put it on the table, I mean, chair."

Such errors also pose a "representational problem" for PLT because the perceptual system begins at best (i.e., using the inner loop) with a phonetic representation of the output. However, lexical substitution errors cannot be detected using a phonetic representation because nothing is phonetically wrong with words that are substituted in error. Unless the perceptual system somehow has prior access to higher level representations that are being developed within the production system, detecting this type of error will not be possible at these higher levels.

The representational problem in PLT and in early editor theories such as that of Motley et al. (1983) is related to the distributed nature of error detection. The editor in early editor theories was seen as using output representations at a relatively late stage of processing, the stage just prior to articulation of the utterance. However, localizing the editing process at this or any other particular point in the production hierarchy is problematic. For example, editing that occurs just prior to articulation must make use of a phonetic representation, but as we have seen, this phonetic code would make error detection and correction at higher (e.g., lexical) levels difficult to explain, a logical inconsistency noted in Motley et al. (1983). However, if the editing process is localized at some higher level, involving say, lexical representations, it becomes difficult to explain detection and correction of errors at all lower (e.g., phonetic and phonological) and higher (e.g., phrase) levels. Such considerations suggest that instead of occurring at only one or two points or levels in the production process, editing must be a distributed or "everywhere" characteristic that permeates the entire output/perception process, from the highest level concepts to the lowest level phonetic units. To capture this distributed aspect of error detection, PLT requires as many loops or production–perception connections as there are units involved in error (i.e., a large number; see Fromkin, 1971).

Finally, PLT fails to capture the special relation between errors and awareness: if the same system processes other-produced and self-produced inputs, including errors, how do characteristics that fail to enter awareness when speech is produced correctly suddenly enter awareness when an error is produced (MacKay, 1990)?

Predictions Derived from PLT

PLT generates several interesting predictions. One is that self-produced errors that violate phonological rules should be detected more quickly than ones that violate lexical rules. The reason is that word errors involve units that are higher in the top-down *production* hierarchy and are thus further from the units within the bottom-up *perceptual* hierarchy that are required for detecting them. Thus, information indicating that an error has occurred should take longer to reach the relevant perceptual detectors in the case of word errors than in the case of phonological errors, so that phonological errors should be detected more quickly than word errors, all other factors being equal.

Another prediction of PLT concerns the many errors that pass unnoticed. For example, speakers fail to detect about 40% of all word substitutions (Nooteboom, 1980), and this large percentage of detection failures may reflect inefficiencies or error tendencies within the perceptual editor, i.e., the perceptual system at large in PLT. However, this explanation implies that perception of self-produced speech and other-produced speech should exhibit identical error tendencies. That is, listeners often misperceive speech produced by others, e.g., mishearing a word such as *Barcelona* as a similar sounding word, *carcinoma* (see MacKay, 1987, pp. 111–119), and under PLT, speakers should tend to misperceive their own error-free speech in precisely the same way. For example, speakers should sometimes misperceive their own speech and produce "pseudocorrections" of the form, "He went to Barcelona, I mean, Barcelona, not carcinoma." Such pseudocorrections differ from repetitions, a common occurrence at all levels of language production (see, e.g., Blackmer & Mitton, 1991), and might be less common than misperceptions of other-produced speech (surely we can hear ourselves better than we can hear other speakers). However, if, as seems to be the case so far, unambiguous instances of pseudocorrection are *never* observed in studies of speech errors, PLT is in trouble.

Moreover, pseudocorrections should be especially prevalent in aphasics with the perceptual deficit known as word sound deafness (Howard & Franklin, 1988). These patients mishear one auditorily presented word as another with high probability and so should frequently make pseudocorrections in their own speech, saying, e.g., "I went, I mean, went," because they misheard the initial *went* as, e.g., *rent*. PLT makes a similar prediction for word meaning deafness, an analogous deficit at the lexical level, where patients miscomprehend one auditorily presented word as another with high probability. However, pseudocorrections have so far never been reported in cases of word meaning and word sound deafness, which is a problem for PLT.

A third set of predictions from PLT concerns detection of errors in inner speech: All other factors being equal, overt speech errors should be easier to detect than the mental errors that occur during internal speech. The reason is that overt speech allows two opportunities for detecting errors: both the internal and the external loops are available for monitoring overt speech, whereas only one (internal) loop is available for monitoring internal speech.

Available data do not unambiguously support this prediction: Dell (1978, 1980) had subjects produce tongue twisters such as "Unique New York" from memory at fixed rates, either aloud or internally, and report the errors that they detected. The same types of errors were reported during internal speech as during overt speech, usually anticipations, perseverations, and reversals of phonological, lexical, and morphological components. More importantly, subjects detected internally generated errors with the same absolute and relative frequency as overtly generated errors, a finding that is difficult to explain in PLT without further assumptions.

However, a more recent study by Dell and Repka (in press) on effects of rehearsing tongue twisters either internally or overtly gave a slightly different pattern of results. Dell and Repka's subjects reported inner slips less frequently than overt slips and more often in syllable-, word-, and phrase-initial positions relative to overt slips. To explain these new results, Dell and Repka invoked an earlier suggestion of Vygotsky and others that speakers are capable of abbreviating their inner speech by omitting noninitial segments in syllables and words, especially words occupying noninitial positions in a phrase. To explain why their results differed from those of Dell (1978, 1980), Dell and Repka then invoked individual differences in this hypothesized process of phonological abbreviation. Whereas Dell and Repka's subjects were all undergraduates, most of Dell's (1978, 1980) subjects were psychology graduate students conducting experiments on short-term memory. Unlike the undergraduates, these graduate students would have been quite knowledgeable about internal speech and its theoretical importance and so may have been less likely to abbreviate their internal speech than Dell and Repka's undergraduates. Again, however, further research on these issues is clearly needed.

A final set of predictions from PLT concerns lexical biases, i.e., greater than chance probabilities of producing lexical errors and of detecting nonword outputs. Such biases are readily explained in PLT and other editing theories and have in fact been demonstrated for both naturally occurring and experimentally induced phonological errors. For example, Dell and Reich (1981) reported that about 53% of the phoneme exchanges in their corpus resulted in words, whereas only about 41% would be expected by chance.

However, editing theories predict such biases for all errors and encounter difficulty when errors *fail* to exhibit lexical bias. Such seems to be the case for blends, e.g., *sotally,* produced as an inadvertent combination of *solely* and *totally*. Collins and Ellis (1991) analyzed a large corpus of blends in German and English and failed to obtain greater than chance lexical outcomes using a variety of rigorous procedures. Coding contamination, e.g., misclassifying as word substitutions those blends that happen to result in an existing word, cannot explain this missing lexical bias because of the careful categorizing procedures and recording of context for the German errors in Collins and Ellis.

If genuine, this missing lexical bias is problematic for editor theories. If the main purpose of prearticulatory editing is to prevent nonlexical outputs from proceeding to articulation (as Baars, Motley, & MacKay, 1975, suggested), then lexical biases should be large and omnipresent. As Collins and Ellis (1991) point out, the fact that lexical bias effects are relatively small at best (12% in Dell and Reich, 1981) is problematic for editing theories: If so many nonwords end up being articulated in error anyway, prearticulatory editing must be so inefficient that its usefulness can be called into question.

PLT is not the only theory for which the missing lexical bias for blends presents a challenge. The explanation of lexical effects proposed by Dell and Reich (1977) and Dell (1986) is also called into question. Contrary to the Collins and Ellis (1991) results, Dell and Reich (1977) predicted that "an acceptable nonword blend is possible but less likely (than a word blend) because it is not a word and there is no single node to support it" (parentheses added). Even Collins and Ellis were hard pressed to explain their missing lexical bias for blends. They proposed an interactive activation model resembling Stemberger's (1985), where units representing the two blending words strongly inhibit other units at the same level. Included among these "laterally inhibited" lexical nodes are ones receiving bottom-up priming from the phonemes making up the blending words. According to Collins and Ellis, this lateral inhibition, depending on its strength and rate of transmission, may wipe out the bottom-up support for lexical outcomes, thereby eliminating the basis for lexical bias in blends.

Why lateral inhibition should have this effect is not clear, even if lateral inhibition increases as a function of degree of semantic relatedness of the mutually inhibiting words. Moreover, the lateral inhibition assumption makes it difficult to see how lexical biases could occur for other errors. Surely a similar process of lexical inhibition would eliminate the bottom-up basis for other, already observed lexical biases resulting from, e.g., phoneme exchanges. Finally, it is unclear how lateral inhibition meshes with the factor that Collins and Ellis and others have postulated as the original source of blends: equivalent priming for the two nodes representing the synonyms that blend. Being equally primed, these two lexical nodes should be inhibiting each other equally strongly. How these two nodes could overcome this mutual inhibition and gain enough additional priming to permit *dual* selection (activation) is therefore unclear.

NODE STRUCTURE THEORY OF ERROR DETECTION

Node Structure theory (NST) is a general theory of processes underlying the perception and production of language; it was not developed specifically for explaining detection of errors. Like PLT, however, NST attempts to explain error detection without introducing additional or special mechanisms beyond those for awareness itself. That is, mechanisms that give rise to awareness in NST are capable of triggering error detection, and although only a general characterization of these mechanisms for awareness and error detection is possible here, these mechanisms have been described in detail elsewhere (See MacKay, 1990; in press-a. See also Eikmeyer & Schade, 1991, and Schade & Lauenstein, in press, for relevant simulations).

Awareness in NST corresponds to prolonged activation of one or more nodes and is truly distributed in nature: Any node that can form new connections with other nodes can undergo prolonged activation and contribute to awareness. Thus, mechanisms for awareness and error detection in NST are closely related to mechanisms whereby nodes form new connections with uncommitted nodes (i.e., nodes whose connections are all so weak that they cannot enable it to become activated): Awareness (prolonged activation) functions to integrate novel combinations of units and occurs only when two or more existing nodes call simultaneously for the formation of new connections to an uncommitted node at some level in the system. Similarly, errors enter awareness only when nodes activated in error call for formation of new connections to an uncommitted node at some level in the system.

Three and only three conditions are necessary to trigger the awareness/connection formation process in NST: novelty, pertinence, and strong convergent priming. I outline these conditions below (see MacKay, 1990, for a discussion of mechanisms and theoretical rationale) and then argue that errors virtually always satisfy the first two conditions (novelty and pertinence) and often satisfy the third (strong convergent priming) in such a way as to enable extremely rapid error detection. Error detection in turn triggers orienting reactions, one of which (cessation of ongoing activity; Neumann, 1987) plays a central role in the *error correction* process.

NST Conditions for Awareness/Connection Formation

The novelty condition. Because of the novelty condition, we become conscious of only what is new, rather than what is old, habituated, or highly familiar, and we form new connections for representing only such novel information. To satisfy the novelty condition in NST, two or more nodes that have never been activated in simultaneous combination before must become activated simultaneously or in temporal overlap. For example, presenting the noun phrase "relevant originality" would automatically satisfy the novelty requirement for a listener who has never heard this particular combination of adjective and noun before.

The pertinence condition. To satisfy the pertinence condition, the novel combination of simultaneously activated nodes must occur in familiar, sequentially related categories. For example, the expression "relevant originality" would meet the pertinence condition if a listener "knows" that "relevant" is an adjective, that "originality" is a noun, and that an adjective followed by a noun constitutes a noun phrase in English. Stated more abstractly, *noun phrase* is a category of nodes that can represent sequences of pertinent categories such as adjective + noun in English (see MacKay, 1990).

Aspects of the phonemic restoration effect illustrate a converse case, where nodes simultaneously activated in novel combination *are not* components of pertinent categories and where awareness and connection formation *fail to occur*. To demonstrate phonemic restorations experimentally, a single speech sound in the magnetic recording for a word is spliced out and replaced by an extraneous noise such as a cough. The tape is then played to subjects who have been instructed to specify which speech sound in the word has been obliterated (Warren, 1982). The remarkable finding is that subjects are unable to accurately make this judgment: they report that all of the phonemes in the word seem intact and that the cough and speech sounds seem to coexist in parallel, as if coming from different spatial locations. Why is the nonspeech sound not perceived in relation to the speech sounds? The reason under NST is absence of pertinence: No categories of nodes exist for representing the sequential combination of a speech sound and a nonspeech sound such as a cough. Speech sounds and nonspeech sounds can simultaneously activate a novel combination of nodes but not pertinent ones that jointly connect to uncommitted nodes so as to trigger new connection formation and awareness of the combination (see MacKay, 1990).

The strong convergent priming condition. Because of the strong convergent priming condition, awareness/connection formation will occur only when the new or uncommitted node receives strong priming that converges from the novel combination of simultaneously activated nodes in pertinent (familiar and sequentially related) categories. This strong convergent priming enables the uncommitted node to achieve prolonged activation (awareness), which in turn strengthens top-down connections to the subordinate nodes (see MacKay, 1990), thereby enabling verbal report, the usual criterion for awareness in psychology.

How Perception and Production Errors Occur in NST

Figure 1 illustrates the hierarchic organization of nodes in the phonological and semantic or sentential systems of NST for producing sentences such as "Frisbees are made of plastic" and "Frisbees are thrown." Perception and production use the same nodes and mechanisms for activating them in NST. Specifically, nodes are activated via a "most-primed-wins" principle in both production (MacKay, 1982, 1985) and perception (MacKay, 1983, 1987, pp. 14–38): the activating mechanism activates the node with the most priming in sequential classes or categories such as noun, adjective, or initial consonant group (see Fig. 1 for other examples). This most-primed-wins principle serves a variety of important functions, but automatically gives rise to errors in perception or production if the appropriate node fails to achieve greatest priming in its category when the most-primed-wins activating mechanism is applied. As a result, some other, more primed node in the category becomes activated in error. This explains why substituted and substituting components in production errors almost invariably belong to the same category or sequential class (the sequential class regularity; see MacKay, 1979, 1987, pp. 59–61): at the sentential level, nouns substitute with other nouns, verbs with

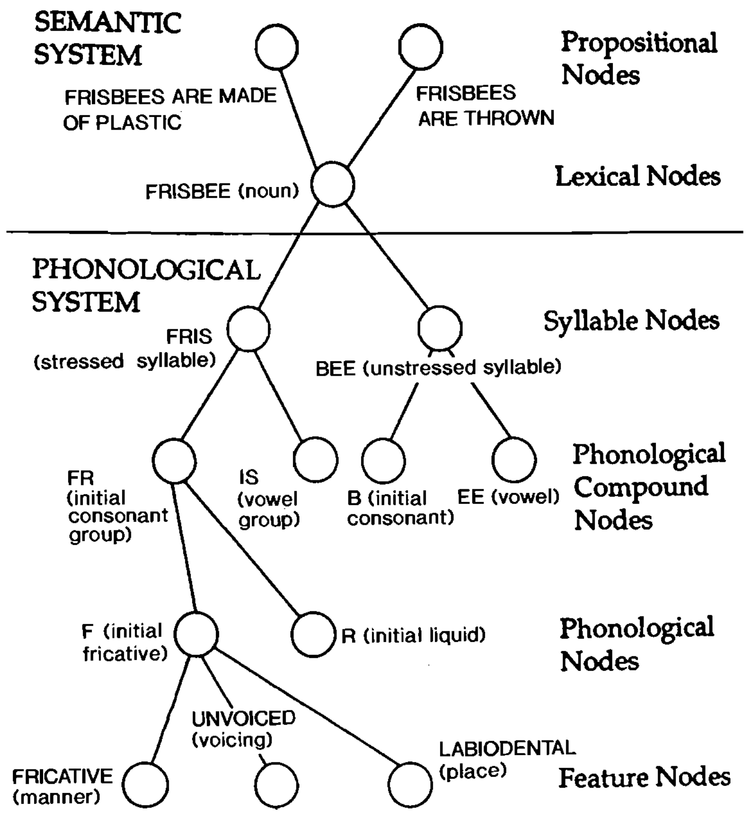

FIG. 1. Plans (node hierarchies) in the phonological and semantic or sentential systems for perceiving and producing the word *frisbee* in sentences such as *Frisbees are thrown* and *Frisbees are made of plastic*. Sequential categories to which the nodes belong are represented in parentheses.

verbs, and not with, say, nouns or adjectives; at the morphological levels, prefixes substitute with other prefixes, suffixes with other suffixes, but never prefixes with suffixes; at the syllabic level, initial consonant clusters substitute with other initial clusters, final with final, but never initial with final; and at the segment level, vowels substitute with vowels, consonants with consonants, but never vowels with consonants. Substitution errors result from competition between nodes for most-primed status within these categories, rather than from competition between activating mechanisms (because both correct and incorrect nodes become activated via the same activating mechanism) or from competition between plans for perception or production (which correspond to preformed hierarchies such as those in Fig. 1; see MacKay, 1982). The sequential class regularity also applies to other classes of errors, including blends (see MacKay, 1972a, 1973), because an activating mechanism (sequence node) can only activate inappropriate nodes within the same sequential category as the appropriate or intended-to-be-activated node.

Errors and the Conditions for Awareness and Connection Formation

Errors always meet the novelty condition in NST because they invariably call for a novel unit *at some level*. By way of illustration, consider the following three errors from Motley et al. (1983). *Crawl space* internally misproduced as *crawl srace* calls for a novel phonological unit because syllable-initial *sr-* does not occur in English; *Dump seat* internally misproduced as *sump deat* calls for a novel lexical unit because *deat* is a nonword in English; and *Fly the plane and buy the boat* internally misproduced as *Fly the boat and buy the plane* calls for a novel propositional unit because the proposition that boats fly is unlikely to have been encountered or stored as a committed node in the past.

Note that errors also meet the pertinence condition because nodes that become activated in error under a most-primed-wins principle invariably fall into familiar sequential categories. In fact, the sequential categories for intended and erroneous outputs will tend to be identical under NST.

The only remaining issue is whether an error will meet the *strong convergent priming* condition required for awareness. Because strength of priming decreases as more connections between nodes are crossed, NST predicts that error detection will be less likely the greater the "distance" or number of connections that separate the nodes activated in error from their uncommitted node.

Table 1 illustrates this concept of distance by means of three hypothetical errors involving transpositions of similar phonological components in inner speech. Consider first the transposition exhibiting minimum possible distance; *cpamped srace* instead of *cramped space*. For speakers of English, no node has been committed to represent the nonoccurring cluster *cp-*, so that as soon as *c*(initial stop) and *p*(initial stop) are activated together in error, strong first-order bottom-up priming converges immediately (distance 0) onto an uncommitted node that is in the category labeled initial consonant cluster and weakly connected to the /k/ and /p/ nodes. This strong convergent priming triggers awareness of the error (i.e., prolonged activation of kp-) together with an orienting reaction that causes output to terminate. Similarly, because no node has been committed to represent *sr*(initial consonant group), strong first-order bottom-up priming con-

TABLE 1
Relations Predicted within NST between the Probability of Detecting Three Hypothetical Transposition Errors and the Distance (Number of Intervening Connections) between the Units Activated in Error and the First Novel Unit (Uncommitted Node) That They Both Prime

Transposition error		Distance	Predicted *P*(detection)
cramped space →	cpamped srace	Low (0)	High
fat lady →	lat fady	Moderate (2)	Moderate
tool carts →	cool tarts	High (4.5*)	Low

* Ambiguous between distance 4 vs 5. See text for explanation.

verges immediately onto another uncommitted node in the category (initial consonant cluster) when *s*(initial fricative) and *r*(initial liquid) are activated together in error, again enabling awareness of the error. Indeed, such "distance 0" errors may be detected so rapidly and so efficiently that speakers can usually stop speaking before these errors appear as muscle movements in the surface output (see MacKay, in press-a; Levelt, 1984). This rapid detection sequence may therefore explain why phonologically unacceptable sequences such as *sr-* and *cp-* rarely appear as errors in overt speech (see Fromkin, 1971). Note also that transpositions offer two independent opportunities for error detection under NST, so that transpositions should be detected more readily than otherwise comparable anticipations and perseverations.

Consider now a transposition error involving moderate distance; *lat fady* instead of *fat lady* (see Table 1). When *l*(initial liquid) and *f*(initial fricative) are activated in error, bottom-up priming converges on two already committed nodes representing the English syllables *lat* and *fa* and only converges on uncommitted nodes that can trigger awareness at the lexical level (because *lat* and *fady* are nonwords). However, because strength of priming decreases with number of connections crossed, awareness is less likely for such distance 2 errors than for distance 0 errors.

Finally, consider the transposition error exhibiting greatest distance; *cool tarts* instead of *tool carts* in the intended sentence *They were moving tool carts down the assembly line* (see Table 1). Here higher level nodes already exist for representing units produced in error such as the segments, *c*(initial consonant group) and *t*(initial consonant group), syllables, *cool*(stressed syllable) and *tarts*(stressed syllable), and words, *cool*(adjective) and *tarts*(noun). And if the speaker happens to have an already committed node for *cool tarts* (noun phrase), error detection could only be triggered at still higher levels. That is, activating *cool tarts*(noun phrase) together with *move down the assembly line*(verb phrase could in principle trigger orienting reactions and awareness of the error if (as seems likely) the speaker lacks an already committed node for the phrase *were moving cool tarts down the assembly line.*

To illustrate more concretely how priming converges over varying distances from sequentially related nodes activated in error onto the uncommitted node that they both prime, Figs. 2 and 3 compare nodes involved in this "high distance" error (*cool tarts*) with those involved in a "moderate distance" error (*sump deat* instead of *dump seat*). Because distance (number of intervening committed connections) is so much greater in the case of *cool tarts,* this error is more likely to fail the strong convergent priming condition and to pass undetected. Note also that a correctly activated lexical node, e.g., *tool*(noun) in Fig. 3, will receive bottom-up priming from its correctly activated subordinate, *ool*(vowel group). However, this bottom-up priming process will stop there because an inhibitory process known as self-inhibition resets priming to 0 and terminates simple activation (but not prolonged activation or awareness; see MacKay, 1990, 1987, pp. 141–164).

In general of course, distance will be greater for errors resulting in real words (Fig. 3) than for errors resulting in nonwords (Fig. 3), so that NST predicts a bias

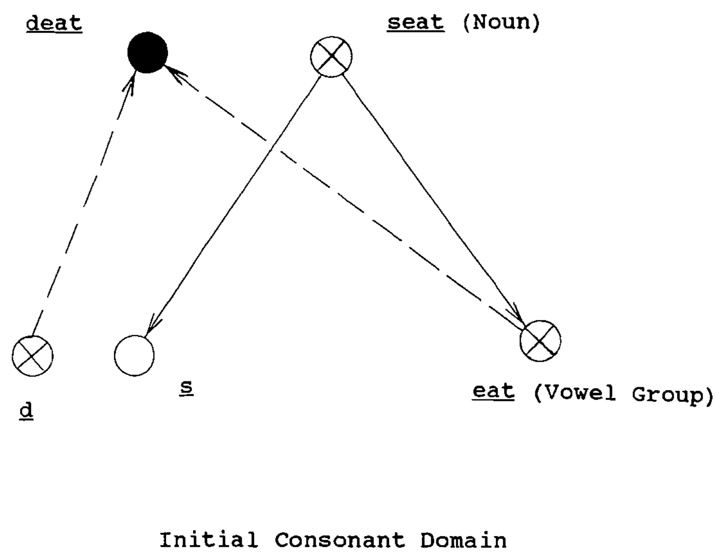

FIG. 2. A critical subset of nodes underlying detection of the phoneme substitution error *deat* for intended *seat*. See text for distinction between primed nodes (open circles), activated nodes (crossed circles), and uncommitted nodes (solid circles).

favoring nonwords in the detection of errors (even blends; see below). Moreover, because errors can sometimes be detected and prevented before they occur, this detection bias could in principle cause a weak production bias *in favor of* word rather than nonword outputs, like the lexical biases observed in, e.g., Dell and Reich (1981) and Baars et al. (1975). Also, because of its complex, indirect nature in NST, this lexical production bias should occur only at relatively slow processing rates when there is plenty of time for detecting and correcting errors internally prior to output. This prediction is consistent with the experimenal observations of Dell (1986) that lexical biases disappear with rapid output rates, although Dell provides a quite different account of this finding.

Finally, it is important to note that unlike incorrect output, *correct* output in NST cannot automatically trigger awareness that the output is in fact correct. Activating appropriate or intended-to-be-activated nodes transmits convergent bottom-up priming to higher level nodes that are not only committed, but have themselves just been activated and are undergoing self-inhibition, which terminates convergent bottom-up priming. Correct output cannot therefore trigger awareness that the output is in fact error-free, which may explain why it takes longer for subjects to correctly determine that they have *not* made an error than that they have (see MacKay, 1987, p. 166).

Blends: A Special Case?

Word blends are a rare type of error that arise in NST when two lexical nodes representing "psychological synonyms" (see MacKay, 1973) have accumulated

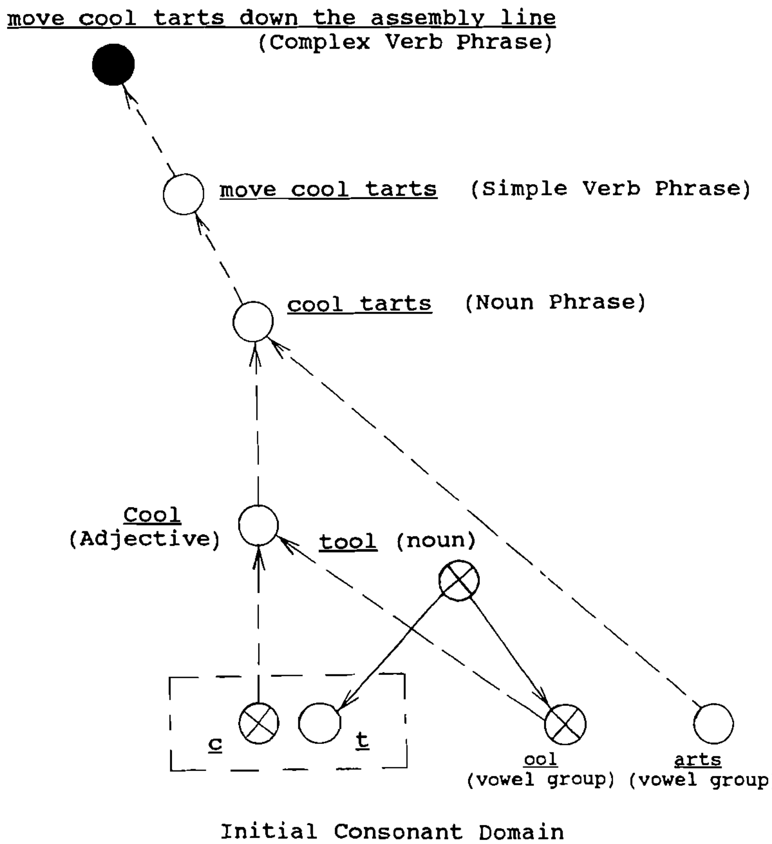

FIG. 3. The maximum number of nodes underlying detection of the phoneme transposition error *cool tarts* instead of *tool carts* in the intended sentence "They were moving tool carts down the assembly line." See text for distinction between primed nodes (open circles), activated nodes (crossed circles), and uncommitted nodes (solid circles).

the same amount of priming at the time when the activating mechanism is applied, so that *both* lexical nodes become activated simultaneously under the most-primed-wins principle (MacKay, 1987, p. 34). As a result, phonological nodes for both words become primed simultaneously and the most primed nodes in the relevant phonological categories become activated automatically under the most-primed-wins principle. Whether the outcome of an internal blend is a word or a nonword is therefore purely a matter of chance. Like other errors, however, blends should be detected with a probability that varies inversely with distance and factors such as whether the outcome is a word, e.g., *They are putting in a new yawn* (*yard/lawn*), or a nonword, e.g., *They are sotally* (*solely/totally*) *responsible*.

Data in support of this distance prediction can be found in Berg (1992), who examined a large corpus of German errors (N = 3158), some of which were detected by the speaker, and others not. Berg's goals were to compare the detect-

TABLE 2
"Distance" and the Probability of Detecting Three Types of Blend Errors: Predicted (Under NST) versus Actual

Type of blend error	Distance	Predicted *P*(detection)	Actual *P*(detection)
Within-morpheme blend	Low	High	.81
Within-word blend	Medium	Moderate	.54
Between-word blend	High	Low	.42

Note. Data are adapted from Berg (1992). Examples: Within-morpheme blends: mohrruben + wurzeln → murzeln. Within-word blends: aushalten + ertragen → austragen. Between-word blends: (1) kommt nicht in die Tuete + kommt nicht in Frage → kommt nicht in die Frage. (2) We're together + I'm with you → We're with you.

ability of blends vs other errors and to compare the detectability of three types of blends: within-morpheme blends, e.g., *mohrruben* and *wurzeln* blended as *murzeln,* a nonword containing a nonmorpheme, *murz;* within-word blends, e.g., *aushalten* and *ertragen* blended as *austragen,* a word consisting of existing morphemes, *aus* and *tragen;* and between-word blends, e.g., *kommt nicht in die Tuete* and *kommt nicht in Frage* blended as *kommt nicht in die Frage,* an unacceptable phrase that contains fully acceptable words. Now, these three categories of blends differ in distance, and as can be seen in Table 2, the observed probability of detection in Berg varied inversely with distance across the three categories, as predicted under NST.

A bias against detecting blends that result in existing words should of course cause a weak lexical bias in production if speakers can detect and prevent blends before they occur. However, two arguments can be advanced that blends are special, and in general more difficult to detect than other lexical errors, and less likely to be prevented before they occur. Because both lexical nodes become activated in blends, the subordinate nodes of both send internal feedback (bottom-up priming) to a just-activated node that is undergoing self-inhibition, and these subordinate nodes become activated without being subordinate nodes of an unactivated or "unintended" node (Schade, 1992, personal communication). In line with this argument, blends were detected significantly less often than other types of substitution errors in Berg's (1992) data: Speakers detected 60% of all blends and only 42% of between-word blends (see Table 2) compared to 93% of word substitutions. However, 93% is a remarkably high detection rate for word substitutions (compare Nooteboom's, 1980, data, discussed above), and this difference requires replication, preferably using experimental procedures for inducing errors. The second argument for the special status of blends follows from an extension of NST discussed later.

The Special Relation between Errors and Awareness in NST

NST readily explains the special relation between errors and awareness noted in the introduction: Although adults *normally* become aware of higher level concepts (words and above) rather than lower level units (articulatory gestures and phonological units making up words and phrases), these lower level units suddenly enter awareness following a low level speech error. The reason under NST is that even phonetic errors such as the slurring of a speech sound constitute instances of pertinent novelty that can call for new connection formation and trigger awareness at phonetic levels. Because nodes activated in error and nodes currently undergoing activation at other levels in the system also represent instances of pertinent novelty that can trigger awareness, the speaker may also become aware of higher level (pragmatic) implications of such low level errors (as argued in the introduction for the slurring error; see also MacKay, 1990).

Detecting Lexical vs Phonological Errors

Bottom-up priming initiates the error detection process in NST immediately after an error at whatever level the error occurs. This means that time required for detecting an error and the probability of error detection should be no greater for phonological substitution errors than for lexical substitution errors, all other factors held constant. However, with distance greater than 0, practice (linkage strength) will normally be impossible to hold constant across phonological vs lexical nodes: Bottom-up connections from existing phonological nodes generally have much greater linkage strength than those from existing lexical nodes (see MacKay, 1982). And because transmission of priming varies with linkage strength (MacKay, 1982), phonological errors will more likely achieve the strength of priming required for novelty detection (awareness), again, all other factors being equal. In this regard it is interesting that correction rate for phonological errors in Meringer's (1908) corpus (as analyzed by Nooteboom, 1980) was 75% and significantly greater than those for comparable types of lexical errors (54%). However, Berg (1992) failed to replicate this basic difference for a large corpus of naturally occurring German errors: In Berg's corpus, lexical errors (93% detection rate) and phonological errors (91% detection rate) were detected about equally often. Under NST, a reanalysis of both sources of data is needed to equate for possible differences in "distance" for lexical vs phonological errors. With distances above 0 held constant, but prior practice free to vary, NST predicts that phonological errors will be easier to detect than lexical errors.

Detection of Other-Produced Errors

It is important to note that other-produced errors cannot be detected in the same way as self-produced errors in NST. To illustrate this difference via hypothetical example (derived from Ericksen & Mattson, 1981), compare perception vs production of the error in "How many animals of each kind did Moses bring on the Ark?" In production, new connection formation and orienting reactions indicating that an error has occurred can be triggered soon after activating the wrong node, *Moses*(proper noun), resulting in a correction such as, "How many animals of each kind did Moses, I mean, Noah bring on the Ark?" However, listeners have no similar basis for detecting an analogous error during perception of other-produced speech: When listening, orienting reactions and node commitment will be occurring 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?"). NST therefore predicts differences between detecting self-produced vs other-produced errors, including the fact that self-produced errors are detected faster than other-produced errors (Lackner & Tuller, 1979). Moreover, lexical substitution errors will be easier to detect than otherwise similar phonological errors when perceiving *other-produced* speech (see MacKay, 1987, pp. 166) but not when perceiving *self-produced* speech (see above).

SIMILARITIES AND DIFFERENCES BETWEEN NST AND PLT

Like PLT, NST can readily account for the speed with which speakers usually detect and correct self-produced errors (Blackmer & Mitton, 1991). Unlike PLT, however, error detection is a distributed or "everywhere" phenomenon in NST: Rather than occurring at only one or two points in the processing hierarchy as in PLT, the error detection process begins in NST at whatever level an error occurs, from the highest conceptual level to the lowest phonological level. Also unlike PLT, NST detects novelty rather than deviations from linguistic rules or standards. Moreover, NST cannot generate pseudocorrections. The reason is that systems for perceiving phonological and lexical errors in NST are not independent of systems for producing these errors, as is the case in PLT: NST uses the same nodes for both production and perception and perceives errors only because they cause convergent internal feedback (priming) that cannot be cancelled (via self-inhibition): However, internal feedback from nonerrors *is* cancelled and cannot cause misperceptions or trigger pseudocorrections.

Like PLT and other theories, NST has an external loop that includes the muscle movement system, airborne and bone-conducted acoustics, and the acoustic analysis system (see MacKay, 1992a). Unlike PLT, however, this external loop carries no new information or opportunities for detecting phonological and lexical errors, so that these errors should be no easier to detect in overt than internal speech. Also, unlike PLT, NST does not predict that detection of self-produced phonological and lexical errors will improve with increases in the amount of external feedback (auditory, kinesthetic, etc.) that is provided or allowed. And of course, NST requires neither "internal loops" for perceiving internal speech nor links between production units and perception units: Production units *are* perception units in the phonological and sentential systems of NST, an assumption that fits nicely with combined production–perception effects, as when masking noise caused a decline in both output fluency and error detection in Lackner and Tuller (1979) (see above).

Why then did masking in Lackner and Tuller (1979) greatly reduce detection of voicing errors, but not place of articulation errors? The special relation of masking to voicing errors is at least as readily captured in NST as in PLT. Under NST, white noise is a special input that resembles aspects of the acoustic signal for distinguishing voiced vs unvoiced speech sounds and so could greatly interfere with (1) perception of voiced vs unvoiced speech sounds (which it does, especially in the range of signal-to-noise ratios from 0 to -18 db; Miller & Nicely, 1955), with (2) production of voiced vs unvoiced speech sounds, and with (3) processing of internal feedback from voicing errors, so that voicing errors are especially difficult to detect (as Lackner & Tuller observed).

WAYS TO FURTHER DEVELOP THEORIES OF AWARENESS AND ERROR DETECTION

We have already noted one way to further develop PLT and NST: to devise tests of their differing predictions. However, this traditional procedure is neither the only nor always the simplest, most direct and trouble-free way to develop a theory (see MacKay, 1992b). Another way is to try to extend the theory to related spheres of knowledge. Both NST and PLT apply primarily to work on speech errors at the lexical and phonological levels. For example, neither theory addresses the problem of utterance level errors such as unintentional instances of telling a secret, insulting someone, or making a fool of oneself, all of which can be much more damaging and result in quite different sorts of repairs than lexical and phonological errors. Even the extensive work on error detection in closely related skills such as typing, handwriting, and reading has been largely overlooked in developing these theories.

However, there are good reasons for attempting to apply or extend current theories of error detection to related cognitive skills. Five such reasons are illustrated below.

General Theoretical Principles and Their Exceptions

General theoretical principles are likely to emerge from applying current theories more broadly because error detection in speech, typing, and handwriting exhibits so many shared characteristics (see MacKay, in press-b). As with speech errors, skilled typists normally detect from 50 to 70% of their typing errors and detect them very quickly: With instructions to stop typing after making an error, typists can usually stop one keystroke after the error (Long, 1976; Shaffer & Hardwick, 1969). Like speakers, typists also seem to detect some errors before fully executing them because keys struck in error are often pressed more lightly than normal (Rabbitt, 1978; Wells, 1916).

If, on the other hand, fundamental differences or exceptions to general theoretical principles emerge from some area of broadened inquiry, these differences or exceptions acquire immediate theoretical interest and motivate further research. Consider, for example, the pseudocorrections predicted by PLT for speech. Although instances of pseudocorrection have never been reported for speech, they *have* been reported when feedback is restricted during transcription typing. Typists in West (1967) received varying degrees of restricted sensory feedback, with instructions to stop typing after making an error of any kind. They then typed /*/ and corrected their error. When prevented from seeing both their hands and their typed copy, some typists (level of skill unspecified) sometimes produced outputs resembling pseudocorrection: they signaled an error and retyped a word that they originally had typed correctly. Extending PLT to typing would therefore have two desirable effects: to intensify or further justify the search for pseudocorrections in speech, and to stimulate further research into the nature of pseudocorrections in typing to ensure that they really involve misperceptions followed by pseudocorrection and not just, e.g., momentary failures to remember the original output or code it as correct.

Missing Variables

Applying a theory more broadly also reveals dimensions or variables that are relevant but missing in a theory. Consider practice, for example, a variable missing in PLT, but not in NST where skill or practice directly influences strength of priming (see MacKay, 1982) and therefore error detectability for errors with distance greater than 0. Preventing typists from seeing their typed copy or their hands or both has an effect on error detection that depends on the skill of the typist. Unlike skilled typists, unskilled typists detect about 30% fewer errors when prevented from seeing their typed copy (Long, 1976; Rabbitt, 1978; West, 1967), and even skilled typists benefit from seeing the keyboard when detecting errors on relatively unpracticed keys such as], $, %, +, @, #, ^, &, *, {, and < (Cooper, 1983).

However, the general effect of practice on the need or usefulness of external feedback in error detection is apparently not strong enough to overcome another general effect, improvement in error detection when peripheral production processes are slowed down, holding internal production processes constant. Thus, pen slips are more often detected and corrected than either speech errors or typing errors because, although handwriting is less practiced, muscle movements for handwriting proceed at a much slower rate than those for more practiced skills such as speech and expert typing (MacKay, in press-b). Also, words are more often left unfinished or abandoned immediately following a slip of the pen than following tongue slips and typing slips (van Nes, 1971), as if the peripheral slowness of handwriting allows writers to detect an error, stop immediately, and begin a word anew. Thus, writers can stop output after detecting the first letter of a transposition and start again, leaving on paper something that is indistinguishable from an anticipatory error (van Nes, 1971). As a result, anticipations may be inflated in number relative to transpositions and perseverations in current collections of pen slips (MacKay, in press-b).

Hidden Theoretical Limitations

Another reason for applying current theories more broadly is that otherwise hidden limitations quickly become obvious. The above analysis suggests that PLT should incorporate not just related cognitive skills, but also practice and rate of output as variables. When this is done, however, PLT makes incorrect predictions. For example, because most outputs are error-free, the perceptual system in PLT will acquire much more practice in monitoring error-free outputs and so should be slower in responding that an output is in error rather than error-free. This prediction contradicts the fact that detecting correct responses takes more time than detecting incorrect responses in skills resembling typing (Rabbitt, 1966;

Rabbitt, Vyas & Feamley, 1975). Moreover, response times tend to be faster for an error correction response than for a correct response, even a correct response that subjects are preprogrammed to simply repeat (Burns, 1965, cited in Rabbitt, 1968).

Another prediction of PLT as extended to handwriting and typing is that error detection will improve depending on how much external feedback is provided or allowed in these skills. This prediction seems to fit novice typing (discussed above), but not skilled typing. Highly skilled touch typists type letter keys as quickly and as accurately and detect as many errors when they can see their typed copy and/or fingers as when they cannot (West, 1967). This failed prediction of extended PLT has implications for original PLT (unextended beyond speech): If increased practice makes external feedback less necessary or useful for detecting errors, increased external feedback should have no effect on error detection in speech, the most practiced of all complex skills (see MacKay, 1982). Thus, either the original PLT is wrong about the relation between external feedback and error detection in speech or, for some interesting but yet-to-be-specified reason, speech and skilled typing make different use of feedback in detection of errors.

Hidden limitations of NST also emerge when NST is extended more broadly. For example, the distance predictions in Tables 1 and 2 consider distance within only *language* systems. However, there exist other closely connected systems that process speech-related concepts in parallel with the phonological and sentential systems during speech production. Examples of such systems are the *visual concept system* for processing, e.g., images of objects, the *connotative system* for processing, e.g., the emotional import or tone of words, and the *auditory concept system* for processing, e.g., intonation, prosody, loudness, speaker identity, and voice quality (see MacKay, 1992a). Figure 4 provides an overview of how the familiar systems for perceiving speech acoustics, phonology, and semantics may be related to one of these parallel systems, the auditory concept system. Psycholinguistics has traditionally focused on the link between the acoustic analysis system, which processes all acoustic inputs, and the phonological and senten-

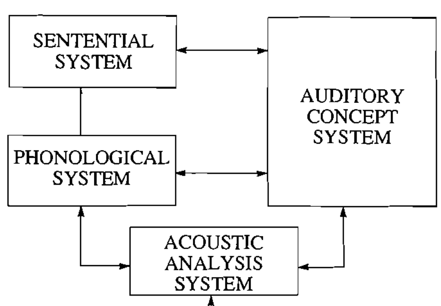

FIG. 4. Connections between the acoustic analysis system, phonological system, and sentential system and the parallel system for processing auditory concepts such as intonation, prosody, loudness, speaker identity, and voice quality (from MacKay, 1992a).

tial systems, which process segments, syllables, words, and their order in sentences. However, the acoustic analysis system also has a link to the auditory concept system that processes other aspects of speech acoustics, e.g., intonation, separately but in parallel with phonological and lexical processing (see Fig. 4).

Parallel processing of errors within these additional systems for representing visual concepts, connotation, and prosody may greatly reduce the distance involved in error detection. By way of illustration, consider again the *tool carts* example in Fig. 3. The *cool tarts* error might be detectable within the visual concept system soon after *cool*(adjective) and *tarts*(noun) are activated in error because, e.g., *tarts*(noun) is directly connected to and would strongly prime the node in the visual concept system representing *tarts* (see MacKay, 1992a; 1987, p. 38). This strong priming could trigger orienting reactions and awareness of the error because tarts are not part of the visual image that accompanies production of the sentence "They were moving tool carts down the assembly line." Similarly, *cool tarts* might be detectable as an error within the connotative system soon after *cool tarts*(noun phrase) is activated if the connotative representation of *cool tarts* and *tool carts* differ in producing this sentence. However, if such an error were *only* detected within the connotative system, subjects would become aware of making an error, but would be unable to specify what the error was, i.e., its phonology. This aspect of extended NST directly contradicts a prediction from unextended NST (see MacKay, 1987, p. 169) and neatly illustrates how the new NST goes beyond the old.

New Directions for Further Research

Extending current theories of error detection to related cognitive skills also suggests new research issues. Because speech perception, speech production, handwriting, typing, and reading have been studied in virtual isolation until recently (see MacKay, in press-b), these literatures contain many gaps that call for further research. For example, it has been well established in studies of skilled typing that the interval immediately following an uncorrected error is usually longer than average and exceeds intervals two or more keystrokes after the error (e.g., Salthouse, 1985, 1986), as if such errors are registered somewhere in the system, perhaps unconsciously. Post-error slowdown is a reliable, but relatively unexplored phenomenon. For example, perhaps post-error slowdown reflects the process that led to error instead of registration processes. Whatever its cause, however, post-error slowdown in speech awaits potential discovery, especially now that temporal characteristics of speech errors are readily measured (see Blackmer & Mitton, 1991).

New Methodological Paradigms

Extending current theories to error detection in related cognitive skills suggests new methodologies or paradigms for further research. For example, paradigms that have been developed for studying how subjects detect other-produced speech errors or mispronunciations (e.g., Cole, 1973) are few and limited in nature. However, interesting paradigms for studying error detection in other cognitive skills exist and are readily adapted to studying error detection in other-produced speech. Consider, for example, MacKay's (1972b) paradigm for studying detection of errors in spelling. Letter strings were presented briefly (for 120 ms) via tachistoscope, and subjects were told that the letter strings were either correctly or incorrectly spelled English words and that their goal was to write down the strings exactly as they saw them. Prior to half of the trials, subjects were also told what correctly or incorrectly spelled word would be presented (but not whether or how it was misspelled).

The main independent variable was the nature of the misspellings presented for detection: phonologically compatible vs incompatible misspellings. Both classes of misspellings involved nonwords formed by substituting a single letter in a correctly spelled word, but phonologically compatible misspellings could be pronounced in the same way as the original, forewarned word (e.g., *werk* for *work*), whereas phonologically incompatible misspellings required a different pronunciation from the original word (e.g., *wark* for *work*). The results indicated that phonologically incompatible misspellings were significantly easier to detect than phonologically compatible misspellings when subjects were told what word would be presented. Even though stimuli were visual, responses were visual (graphemic), and instructions emphasized report of visual input (what was seen), subjects must have coded the stimuli phonologically because detection was facilitated for phonologically incompatible misspellings relative to phonologically compatible misspellings.

MacKay (1968) and McCusker and Gough (cited in Gough & Cosky, 1977) also observed this effect of phonological (in)compatibility when subjects attempted to detect errors in rapidly read sentences resembling "Nobody knew thet the werk was compleated on the new buildung." And so did Daneman and Stainton (1991), apparently independently. Interestingly, however, with tachistoscopic presentation of individual words in MacKay (1972b), the difference between phonologically compatible vs incompatible misspellings disappeared when subjects were not told what word would be presented: With no advance warning, exactly the same phonologically compatible strings were as easy to detect as phonologically incompatible ones. Expecting a particular word was what made phonologically compatible misspellings difficult to perceive: by themselves phonologically compatible strings were as easy to perceive as phonologically incompatible strings. It was as if instructing subjects what word would be presented provided an additional means of detecting errors, based on the phonological novelty arising from the mismatch between the presented and the expected forms within the phonological system.

This 1972 finding therefore illustrates the general concept discussed above, that parallel processing can enhance error detection in closely connected systems. Here the closely connected parallel systems are the phonological and orthographic systems, which connect with the visual analysis system and with one another in the same way that the phonological and auditory concept systems connect with the acoustic analysis system and with one another (see Fig. 4). The visual concept system, the auditory concept system, and the connotative system may likewise enhance detection of speech errors in this same way. For example, consider lexical errors such as the substitution of *chair* for *table:* When someone activates the node for *chair* when they intended to say *table,* novelty (and error) could also be detected in parallel within the visual concept system because *chair* calls for a new visual image of the situation. Note, however, that blends may be special in this regard because they involve words that are conceptually and connotatively indistinguishable: The two lexical nodes that are simultaneously activated when blends occur do not generally call for the formation of new nodes in other, parallel representational systems, e.g., the visual concept system. And this may explain Berg's (1992) observation that blends are in general more difficult to detect than other lexical errors in spontaneous speech.

Interestingly, parallel systems such as the connotative system can in principle influence muscle movements during speech production, causing, e.g., a change in voice tone, and these influences will be independent of the main determinants of muscle movement, i.e., the sentential and phonological systems. Such independent or parallel effects could negate the original assumption of unextended NST that the external loop *never* carries new information or opportunities for detecting phonological and lexical errors. For example, novelty detection within the connotative system during error production could directly influence voice quality in the muscle movement system (see MacKay, 1992a), causing, e.g., a quaver in the voice. This altered voice quality can provide additional cues for detecting overtly produced errors within the sensory analysis and auditory concept systems, cues that are not available for errors in inner speech.

Returning to detection of spelling errors, a different subclass of phonologically incompatible misspellings in MacKay (1972b) illustrates another concept discussed above, that subjects can become aware of an error, but be unable to specify the precise nature of the error. The subclass was labeled "new-word misspellings" because the error (letter substitution) resulted in another existing word, e.g., *herd* misspelled as *hard.* When subjects received no warning as to the original or correctly spelled word, they correctly recognized these new-word strings more often than any other class of misspellings. Unlike other phonologically incompatible errors, however, advance warning made new-word strings significantly *more difficult* to detect: Subjects usually responded incorrectly either with the forewarned, correctly spelled word or with a different, but correctly spelled word. It was as if subjects had become aware that new-word misspellings were words but, due to the brief exposure time, were unable to tell which words they were. This finding suggests the possibility that a more abstract process of error detection can take place in some system that operates independently but in parallel with the phonological and orthographic systems. Whether this abstract parallel system corresponds to the connotative system is of course unknown at present. However, if the "new-word effect" is neither artifactual nor limited to (mis)spelling detection, it calls for new or modified theories of lexical decision as well as error detection.

What new methodological paradigms do misspellings suggest for studying detection of other-produced errors in auditorily presented speech? In one promising paradigm the subject's task is to identify acoustically presented forms that correspond to mispronounced words and phrases. Subjects are verbally warned or not warned what mispronounced word or phrase will be presented, and the mispronunciations will all differ phonologically from the forewarned word or phrase. Some of these phonologically incompatible mispronunciations will result in nonwords and others will result in words, but all will differ in systematic ways from the phonology of the original, forewarned word, e.g., *conTENT* instead of *CONtent* (a "new-word" mispronunciation), and *REpent* instead of *rePENT* (a "nonword" mispronunciation). By varying the type of error or difference between the expected vs presented word (e.g., misplaced syllabic stress in the above examples), this paradigm can be used to determine detectability of different types of other-produced speech errors, including blends. And by varying meaning, syntax, voice quality, and connotation of the expected word, this paradigm can determine effects of semantic, syntactic, prosodic, and connotative (in)compatibility on error detection.

CONCLUSION

The time seems ripe for examining relations between errors and awareness: There exist interesting phenomena in this area, and relatively well-specified theories that make contrasting predictions regarding error detection. There also exist relatively unexplored paradigms for studying error detection in speech, typing, and reading. Finally, applying current theories of error detection to related cognitive skills seems warranted. Because speech, handwriting, typing, and reading have been studied in almost complete isolation in the past, there exist clear gaps that warrant exploration to determine whether error detection exhibits general regularities that span these related skills, and if not, why not. The outcome will be a more general understanding of error detection that promises to provide an important window on mechanisms underlying awareness.

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