

A restricted interaction account (RIA) of spoken word production: The best of both worlds

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Theories of spoken word production generally assume that mapping from conceptual representations (e.g., [furry, feline, domestic]) to phonemes (e.g., /k/, /æ/, /t/) involves both a meaning-based process and a sound-based process. A central question in this framework is how these two processes interact with one another. Two theories that occupy extreme positions on the continuum of interactivity are reviewed: a highly discrete position (e.g., Levelt, Roelofs, & Meyer, 1999), in which the two processes occur virtually independently; and a highly interactive position (e.g., Dell et al., 1997) in which the two processes exert considerable mutual influence over one another. Critical examination of the empirical data reveals that neither position can account for the full range of findings. An alternative position, the restricted interaction account (RIA), is described. By combining aspects of both highly discrete and highly interactive accounts, RIA can account for the existing empirical data, as well as for more recent challenges to interactive accounts.

Theories of single word production generally assume that two cognitive processes are required for mapping from a conceptual representations (e.g., [furry, feline, domestic]) to the set of phonemes used to communicate that concept (/k/, /æ/, /t/). The first process is meaning-based (semantic) and involves the selection of a particular word to express a nonverbal concept. The second is sound-based (phonological) and involves retrieving the phonemes that correspond to the selected word (Butterworth, 1989; Garrett, 1982). Although there is agreement on this general characterisation of the two processes, there is considerable controversy regarding how the two processes relate to one another. Some researchers claim that they are independent, with semantic processing strictly preceding phonological processing (e.g., Levelt et al., 1999). These are referred to as “discrete” or “componential” theories of spoken word production. In contrast, “interactive” theories propose that semantic and phonological processes overlap in time and can influence one another (e.g., Dell et al., 1997). A good deal of the literature in spoken production has focused on the contrast between these two types of architectures. But because each of these theories has been able to account for a number, but not all, of the relevant empirical findings, this debate has yet to be resolved (e.g., Dell & O’Seaghdha, 1991¹; Levelt et al., 1991).

¹ It is important to note that the theory proposed by Dell and O’Seaghdha (1991) (as well as Dell et al., 1997), is not the most interactive theory one could propose (e.g., in the domain of reading, see Plaut & Shallice, 1993).

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Rather than assume that discreteness and interactivity correspond to categorical distinctions, we propose to examine the relationship between semantic and phonological processes by assuming that there is a continuum of interactivity. Highly discrete and highly interactive theories represent extreme points on this continuum; a number of intermediate positions are possible (see Rapp & Goldrick, 2000, for a discussion of the notion of a continuum of interactivity). This paper describes one such intermediate position—the restricted interaction account (RIA)—which allows for interaction but selectively restricts it. By combining aspects of the highly discrete and highly interactive positions, RIA can more successfully account for the existing facts (Rapp & Goldrick, 2000).

To motivate RIA, we first examine highly discrete and interactive theories and carry out a fairly extensive review of the data that are problematic for each. We then show that RIA has the necessary and sufficient features to account for the existing empirical findings and, furthermore, that it can be extended to account for more recent challenges (Nickels, 2000).

A GENERIC TWO-STAGE FRAMEWORK

Theories of spoken word production differ not only in terms of the degree of interactivity that they incorporate, but also with regard to a number of representational and architectural issues. In order to specifically focus on differences among the theories regarding discreteness/interactivity we adopt a “generic” architecture that abstracts away from many of the representational differences among current theories. To motivate this generic framework, we first briefly review certain prominent theories of spoken word production.

Theories of spoken word production: Representations

Most accounts of spoken word production assume a spreading-activation architecture, whereby processing involves sets of units or nodes that accumulate activation and transmit it to other units. The sets of units represent different types of information. Most theories assume separate sets for semantic, syntactic, and phonological information; theories differ, however, in other regards. We briefly review the proposals of Levelt et al. (1999), Dell et al. (1997), and Caramazza (1997).

Levelt et al.’s (1999) proposed architecture involves several different representational types: conceptual nodes, amodal lemmas, syntactic features, morphemes, and phonemes (Figure 1A). Conceptual nodes are unitary representations of lexical concepts. These are followed by amodal lemma nodes (common to speech and spelling) that correspond to lexical representations. Lemmas represent syntactic information (such as a word’s grammatical category) while at the same time serving as a link between conceptual and form information. Following the lemma level, there is a modality-specific morphological layer that connects to nodes representing the phonemes themselves that make up the words (see also Levelt, 1989; Roelofs, 1992, 1997).

Dell et al.’s (1997) architecture differs in two major ways from that of Levelt et al. (1999) (Figure 1B). First, Dell et al. assume that conceptual information is represented over a set of semantic feature units rather than by a single node for each concept. Second, Dell et al. do not assume a morphological layer. Lemmas (representing syntactic information) map directly onto phonemes (see also Dell & O’Seaghdha, 1991, 1992; Harley, 1993; Stemberger, 1985).

Caramazza (1997) shares Dell et al.’s (1997) assumption of distributed semantic features, but does not share Dell et al.’s or Levelt et al.’s assumption of an amodal lemma

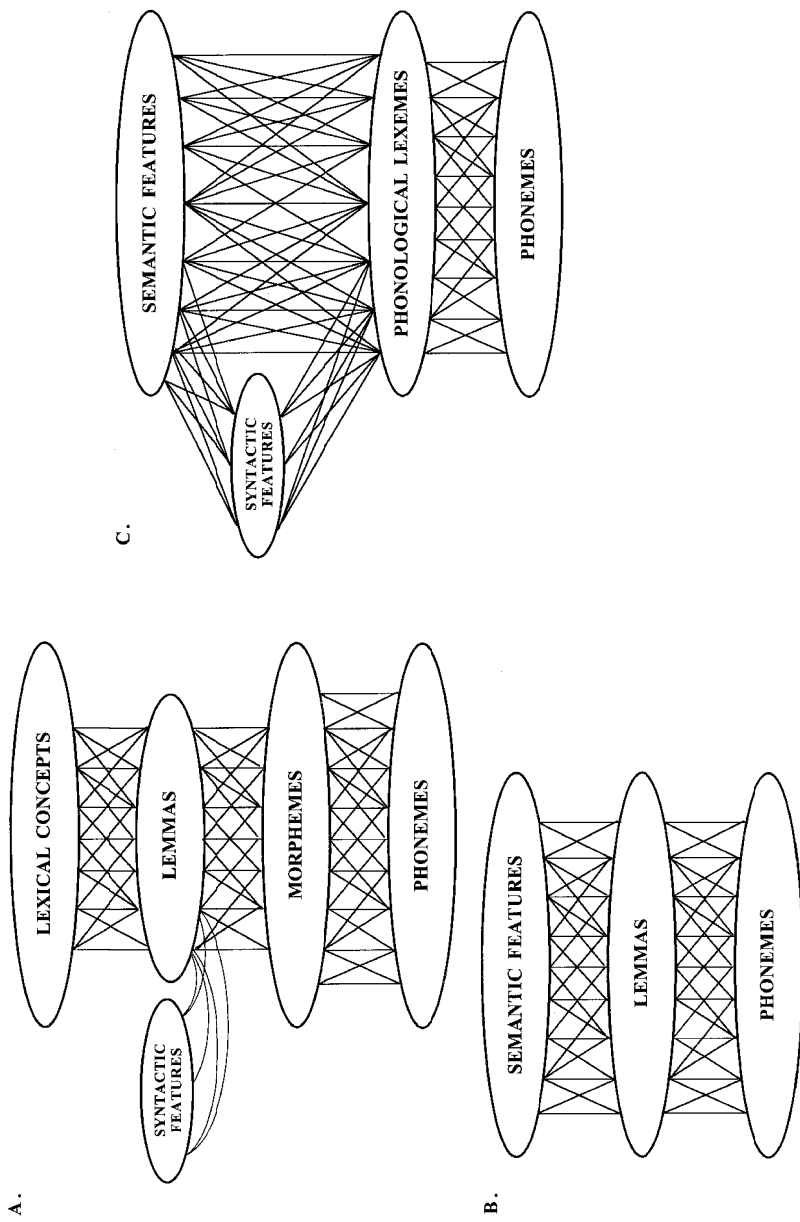


Figure 1. Representational characteristics of three theories of word production. (A) Levelt et al. (1999): Unitary concepts map onto amodal lemmas; these map onto syntactic features and morphemes; the morphemes then map to phonemes. (B) Dell et al. (1997): Distributed semantic concepts map onto amodal lemmas (specified for grammatical category), which map onto phonemes. (C) Caramazza (1997): Distributed semantic concepts map onto phonological lexemes (as well as syntactic features); the lexemes then map onto phonemes.

level (Figure 1C). Instead, Caramazza argues that situated directly between semantic and phonemic representations there is a modality-specific lexical representation: a phonological lexeme. Syntactic information is represented in a separate network that does not have to be addressed in order to activate form information. Form information can be accessed directly from semantics.

Generic representational assumptions

A complete review of the debate among these theories is beyond the scope of this paper. In order to better focus on the differences among these theories regarding discreteness/interactivity we adopt a generic architecture that emphasises their common assumptions (Figure 2). We believe that the conclusions we reach regarding discreteness and interactivity are unaffected by this consolidation of the different theories.

First, we adopt a distributed semantic level of representation. All theories assume that there is a semantic level of representation that encodes similarities among different concepts. Similarity could be implemented through a linked set of concept nodes (where the links represent semantic relatedness) or through a set of shared semantic feature nodes (where feature overlap represents semantic relatedness). We have chosen the latter.

The semantic level is followed by an L-level: a lexical level that mediates between semantics and phonology. Note that all of the theories we have reviewed assume mediation by one or more lexical levels. The units at the L-level could be either modality-specific (e.g. lexemes, as in Caramazza, 1977) or modality-neutral (e.g., lemmas, as in Levelt et al., 1999); for our purposes it will be unnecessary to specify which.

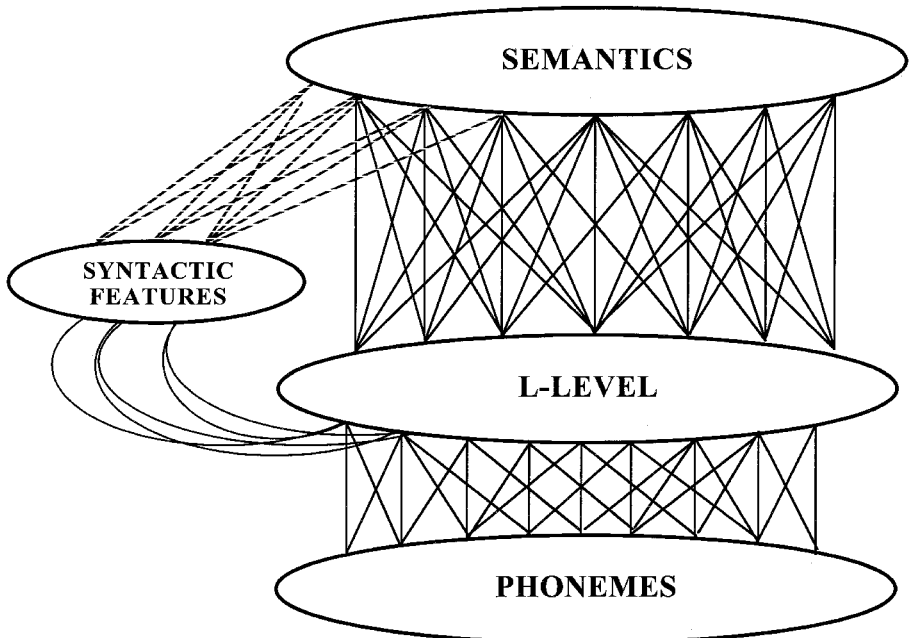


Figure 2. The generic two-stage account of spoken naming. Distributed semantic features map onto lexical nodes which, in turn, map onto phonemes. Syntactic features are connected to lexical nodes and may be connected to semantic nodes.

Third, we assume that the L-level is linked to a set of syntactic features. These may specify such things as grammatical category and: gender, number, count/mass (for nouns); or transitive/intransitive, form of the auxiliary, etc. (for verbs)². This captures the fact that all current theories assume that the selection of a word to express a concept is at least sensitive to the grammatical category of the word and is affected by the syntactic demands of sentence generation³. In addition, we remain neutral with respect to the relationship between syntactic features and semantic units (indicated by the dashed sets of connections). In a theory where syntactic features can be accessed independently of L-level representations (e.g., Caramazza, 1997), the dashed connections would be present. If syntactic features are tightly integrated into L-level representations (e.g., Levelt et al., 1999), the dashed connections may be absent (although see Figure 6b in Levelt et al., 1999).

Finally, the L-level is followed by a set of phoneme-level units, something assumed by all of the theories.

Generic processing assumptions

As indicated earlier, lexical retrieval in spoken word production is assumed to involve two *types of processes*: semantically and phonologically based. These relate, more or less directly, to two *temporal stages* of processing: Stage 1 and Stage 2. Within the generic architecture, we define these as follows:

Stage 1: begins with the activation of semantic feature units and ends with the selection of an L-level unit (corresponding to selecting a word to express a lexical concept).

Stage 2: begins with the activation of L-levels units and ends with the selection of specific phonemes (retrieving the phonemes that correspond to the selected word).

Essentially, discrete and interactive accounts differ in the extent to which phonologically based processing contributes to the outcome of Stage 1 and semantically based processing contributes to the outcome of Stage 2. Adopting a generic architecture allows us to examine these differences while keeping constant all other representational and processing features. For this reason our conclusions will *not* have implications for the various debates concerning distributed versus unitary semantic concepts, modality-specific or modality-neutral lexical nodes, etc.; they speak only to the relationship between semantic and phonological processing during spoken word retrieval.

In the following three sections we evaluate three theoretical positions (a highly discrete account, a highly interactive account, and RIA—the restricted interaction account) with regard to their ability to account for key sets of facts. In each section we describe the processing assumptions of each theory in more detail; here, we will just briefly mention the principal features of each. In the highly discrete account, semantic and phonological processing are entirely independent: that is, there is no activation of the phonological level until an L-level node has been selected and once phonological

²Note that the set of syntactic features may be structured. For example, Caramazza (1997, footnote 4) makes distinctions among these various types of grammatical features depending on the degree to which they are semantically determined.

³In fact, if sentential syntactic processes are engaged they may provide input directly to the syntactic feature nodes. This form of input is not represented in the generic architecture but could be depicted by an arrow into the syntactic nodes, originating from syntactic processes that are outside the word production system.

encoding has begun it is not influenced by activity elsewhere in the system. In contrast, under the highly interactive account, semantic and phonological processing overlap extensively as activation can flow down to all representational levels and back up again throughout the process. Finally, under RIA, both semantic and phonological processes are able to influence one another in a limited manner; this is because while there is feedback from the phoneme level to the L-level, there is no feedback from the L-level up to the semantic level; furthermore the strength of the feedback from the phoneme level is also limited.

A HIGHLY DISCRETE ACCOUNT

A strictly serial, discrete account assumes that all semantic processing is completed before any phonological processing begins. In the generic architecture, these assumptions are implemented by greatly restricting activation flow.

Stage 1: Processing begins with the activation of semantic features associated with a lexical concept (e.g., for the concept <CAT>⁴: four-legged, animal, pet). Activation from these features spreads to the L-level. During this stage syntactic feature activation could take place either directly through activation from semantics (in theories where the dashed connections are present), or indirectly through activation from the L-level, or through both. The result is that the target (CAT) and its semantic and syntactic neighbours (DOG, RAT) are activated. This is shown in Figure 3. During this time, no activation is passed on to the phoneme units: they are inactive. Stage 1 ends with the selection of the most active L-level unit (if all goes well, this would be CAT).

Stage 2: Only the selected L-level unit sends activation down to its phonemes (/k/, /æ/, /t/; Figure 3). Thus, neither semantic nor syntactic neighbours of the target are active during Stage 2. Processing ends with the selection of the most active phonemes.

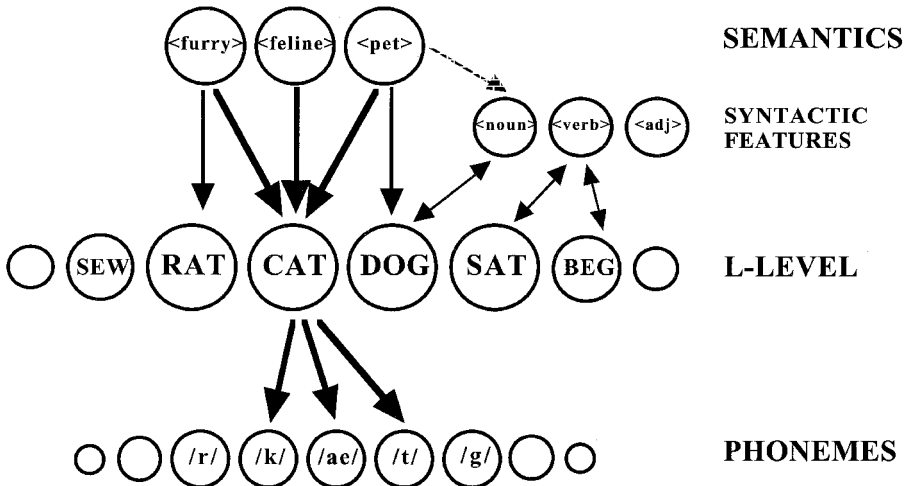


Figure 3. The highly discrete account. Thick arrows denote activation flow involving the target; thin arrows denote activation flow involving its lexical neighbours.

⁴Note that throughout the paper, a semantic concept will be denoted as <CAT>. The L-level unit for the concept will be denoted as CAT, and /k/, /æ/, /t/ will denote the phonological outcome.

This position regarding the relationship between Stage 1 and Stage 2 processing is closest to that of Levelt et al. (1999)⁵. In this theory, *all* Stage 1 processing precedes *all* Stage 2 processing.

Challenges for the highly discrete position

The discrete position can account for a large body of empirical results in word production (see Levelt et al., 1999, for a review). However, a number of findings have been claimed to be problematic for such an account. Here we review the evidence from errors produced by normal or aphasic subjects, focusing on: mixed error effects, the effect of lexical variables on formal errors, and lexical bias. Other relevant sources of evidence that we will not discuss include investigations of the time course of semantic and phonological processing; for a review see Staareveld (2000).

Mixed error effects

If errors occur during Stage 1, they will almost certainly be semantic errors. Semantic neighbours (e.g., <CAT> and <DOG>) have overlapping representations at the semantic level. Activation of the target's semantic representation will therefore activate not only the target's L-level unit, but also units corresponding to its semantic neighbours. Thus, if an error occurs during L-level selection, these semantically related neighbours (pre-activated by semantic features) will be more likely to be selected than L-level units corresponding to words semantically unrelated to the target. If CAT is the target, DOG will be a more likely error than SEW⁶.

Note that during Stage 1, a phonological L-level neighbour of the target (e.g., SAT for the target CAT) is no more likely to be selected than any other semantically or syntactically unrelated word (SEW). This is because all semantically driven processing is complete before any phonological processing begins. At the point of L-level selection, there is no special advantage for phonological neighbours.

In contrast, during Stage 2 the predominant error type will be phonological. Activation of the target's phonemes will necessarily increase the probability that an error will share target phonemes. If /k/, /æ/ and /t/ are being activated and something goes wrong at the point of phoneme selection, then /s/, /æ/ and /t/ will be a more likely outcome than /b/, /ε/ and /g/ (see Figure 3). However, as only the selected L-level unit (CAT) sends activation on to the phonemes, semantically related responses have no special advantage during Stage 2. That is, the phonemes /d/, /l/, /g/ are no more likely to be active than the phonemes /b/, /ε/, /g/.

In sum, under the highly discrete account, Stage 1 errors are based only on semantic similarity, and Stage 2 errors are based only on phonological similarity. Importantly, this is not to say that Stage 1 errors will bear only semantic similarity to the target, and Stage 2 errors will bear only phonological similarity to the target. There is, of course, some probability that a semantic error will, by chance, be formally similar to the target, and also that a phonological error will, by chance, be semantically related to the target. For

⁵Levelt et al. (1999) allow for the possibility that two L-level units (corresponding to close synonyms) may be selected, leading to the phonological encoding of more than one word. This can be seen as an extremely limited version of cascading activation (to be discussed later).

⁶Of course, if one assumes feedback from syntactic features to all L-level nodes sharing that syntactic category, all words belonging to the same syntactic category as the target will also be activated. However, as this accounts for only a small amount of the total activation, they will be very weak competitors.

example, if the target is CAT, RAT will be as active as DOG at the L-level, and thus just as likely to be mis-selected. In addition, its phonemes /r/, /æ/, /t/ will be as active as the phonemes /s/, /æ/, /t/ at the phoneme level (and thus just as likely to be mis-selected). Under the highly discrete account, the rate of these *mixed errors* (words that are both semantically and phonologically similar to the target) will consist of the sum of these two independent error possibilities. In a discrete system, mixed errors will occur, but at rates no greater than would be expected by chance during L-level and phoneme level selection.

Does the rate of mixed errors actually produced by speakers correspond to rates that would be predicted by chance? A difficult issue has been determining the chance rate predicted by the highly discrete account. Two types of error analyses have been performed: analyses of predicted versus observed *rates* of mixed errors; and analyses of predicted versus observed *extent of phonological overlap* between targets and errors.

Error rate analyses. Analyses based on error rates typically assume that a highly discrete theory predicts the following (Martin, Weisberg & Saffran, 1989; Plaut & Shallice, 1993; Shallice & McGill, 1978):

chance rate of mixed errors = (1) the rate of (semantic) errors at the L-level expected to share phonology with the target + (2) the rate of (phonological) errors at the phoneme level expected to share semantics with the target + (3) some correction for the possibility that errors occur at both levels on some trials (e.g., a semantic error followed by a phonological error)

A number of analyses based on these assumptions have concluded that observed rates of mixed errors produced by normal subjects do indeed exceed chance estimates (Brédart & Valentine, 1992; Martin et al., 1989; but see Levelt, 1983).

These studies examined errors produced by subjects who were asked to name items from highly constrained and easily identifiable target sets—Martin et al. used colour names, while Brédart and Valentine used famous faces. This was done in order to determine the opportunities for different kinds of errors. However, Levelt (1992) argued that if we assume that subjects performed the task by holding all members of the (necessarily) limited response set in working memory, then the mixed error effect could be accounted for by confusions within the working memory system. In that case, the mixed error effects would not necessarily reflect properties of the word production system, but rather the interaction of items within working memory.

Phonological overlap analyses. Phonological overlap analyses examine whether the degree of phonological overlap observed in semantic errors is greater than would be expected by chance. This type of analysis has been used with spontaneous error corpora (either from aphasic or normal subjects) on those occasions when rate cannot be determined because the number of items attempted is unknown. Chance rates of target/error overlap are established by calculating the degree of phonological overlap expected by randomly pairing any two words⁷. If the observed degree of target-error overlap in the error corpus exceeds the randomly observed rate, it is assumed that there is a significant mixed error effect. A number of studies using this sort of analysis have reported

⁷ Either through calculation of long-term probabilities of errors (e.g. Dell & Reich, 1981) or through Monte Carlo generation of target-error pairs (e.g. Best, 1996).

significant mixed error effects in normal subjects (Dell & Reich, 1981; Harley, 1984; Martin et al., 1996; but see del Viso, Igoa & García-Albea, 1991; Igoa, 1996) as well as in aphasic subjects (Blanken, 1998; Dell et al., 1997; Martin et al., 1996; but see Best, 1996; Nickels, 1995).

Somewhat problematic for these findings is the fact that this method of calculating chance does not take into account the full set of errors that might be produced. In the studies just listed, chance phonological overlap is estimated by randomly pairing *words*. This analysis therefore implicitly assumes that the only potential error types are word substitutions. This is true of errors that arise in L-level selection, where only word outcomes are possible. However, errors may arise at multiple levels in the production system. In particular, they may occur during *phoneme* selection (where outcomes can be words or nonwords). This would not be a problem if we could assume that none of the errors in the corpora had been generated at the phoneme level. However, given that there is no reason to rule out the possibility that errors were generated at the phonological level, these analyses may underestimate chance rates of phonologically related word errors. Such an underestimation would, in turn, result in an overestimation of the significance of the observed mixed error effect.

Rapp and Goldrick (2000), in their analysis of the semantic errors of an aphasic subject, corrected for multiple sources of mixed errors by removing all mixed errors that could have arisen during phonological processing. After this correction, the subject (CSS) still exhibited a highly significant mixed error effect. Specifically, CSS's semantic errors shared 26.9% of their phonemes with their targets, whereas a mean overlap of 12.9% would have been expected from a random pairing of words.

In sum, a number of empirical results indicate that mixed errors occur at rates greater than would be expected by a highly discrete theory—a true mixed effect. Although a number of these results can be questioned, at least one study addresses the full set of concerns that have been raised (Rapp & Goldrick, 2000).

The prearticulatory editor. Thus far we have assumed that the mixed error effect arises internal to the lexical retrieval process. An alternative possibility, however, is that the mixed error effect results from the failure of an external mechanism such as a *post*-retrieval “editor” whose mission it is to intercept errors before they are articulated (Baars, Motley, & MacKay, 1975). Within a highly discrete account, the prearticulatory editor would evaluate the output of phoneme selection and determine if it corresponded to the intended word. One common account of this mechanism is that it makes use of the language comprehension system (e.g., Levelt, 1983⁸). According to this view, outputs of the production system are processed by the comprehension system before articulation. When the comprehension system detects an error, word retrieval is attempted anew; when the comprehension system fails to detect the error, it is produced. In order to explain the mixed error effect, one must assume that the editor is not perfect and, furthermore, that the likelihood of missing an error is affected by its similarity to the target. Thus, errors that are both semantically *and* phonologically similar would be more likely to be missed by the editor than errors that are either phonologically or semantically similar to the target—giving rise to a mixed error effect.

The proposal is intuitively appealing because it is certainly true that we are capable of examining our intended output before actually producing it; nonetheless the proposal has a number of important shortcomings.

⁸See Postma, 2000, for a review of this and other theories of error monitoring.

First, it is quite vague. How does the editor keep track of the intended target? Is a record of the intended target maintained at each level of representation (conceptual, lemma, and form)? Or only at the conceptual level? How do the similarity effects actually arise? Given these questions, as pointed out by Dell and Reich (1980) and Martin et al. (1989), current formulations of the editorial mechanism (or mechanisms) are overly powerful, unconstrained and, at least in the case of multiple editors (De Smedt & Kempen, 1987; Laver, 1969, 1980; Mattson & Baars, 1992), rather unparsimonious.

Second, although we are capable of examining intended output before production, it is not clear that we do this routinely or even often. A great number of aspects of language production can, at least in principle, be monitored. For example, Levelt (1989) proposed that speakers can evaluate their production to determine whether or not it corresponds to the intended message or makes sense within the discourse context, as well as for social, lexical, syntactic, morphological, and phonological acceptability. However, it is not the case that speakers *always* monitor all of these aspects of production, given that monitoring is demanding of attentional resources. Proponents of an editor therefore typically do not assume that it is always engaged or fully engaged, varying according to the speaker's attentional state. Once one makes this assumption, it is impossible to determine if the errors that have entered the corpora or collected experimentally were the result of editor failures or were produced by the production system on occasions when the editor was not engaged. To the extent to which the latter is true, mixed errors would reflect the natural output of the production system and the mixed error effect would remain problematic for highly discrete accounts.

Finally, in the case of the aphasic data collected in the picture-naming task, positing an automatic prearticulatory editor (one that is always engaged) would require assuming deficits to both the production system and the editor. Given that normal subjects virtually never produce errors in untimed single word production task, it would appear that a prearticulatory editor is normally very efficient at intercepting errors in a task such as single word picture naming (where attention can be fully engaged). In the context of such robust editing, a deficit to the production system should either result in very few errors or no errors at all⁹. If the production deficit is so severe as to preclude correction, errors should be produced but they should not be biased in any particular direction. Therefore, in order to account for the large number of mixed errors made by some of these individuals, proponents of the automatic editor must posit two deficits: one to the production system, and another to the editor which fails to intercept mixed errors, even under optimal conditions.

These problems render the prearticulatory editor a rather unsatisfactory account of the mixed error effect. As we discuss later, the editor is often proposed as means for accounting for a number of other findings that are problematic for the highly discrete account. We will not repeat the arguments we have presented here, but we note that in each case, similar objections to the editor proposal can be raised.

Lexical effects on formal errors

There is some evidence that word-level (lexical) variables may influence phonologically based errors which, under the highly discrete account, arise only during Stage 2. Such influences would clearly contradict the predictions of a highly discrete

⁹Another possibility is that even though the editor is always engaged during *normal* processing, brain damage reduces attentional resources so that the editor is not always active. In this case, it would be unclear whether mixed error effects reflected the operation of the editor or the production system itself (see earlier).

account (which assumes that Stage 2 processing is insensitive to lexical variables). We review evidence regarding the influence of syntactic category, lexical frequency, and word shape on formal errors (word errors that are phonologically, but not semantically, similar to the target).

Syntactic category preservation in formal errors. According to the assumptions of the highly discrete theory, syntactic processing is involved in Stage 1 selection of an L-level unit (at least in part to ensure that a syntactically appropriate word is selected). However, syntactic information is not involved in Stage 2 processing, as that begins only after an L-level item has been selected. Given, therefore, that formal errors arise only after L-level selection, they should exhibit no tendency to preserve the syntactic attributes of the target. For example, if the noun /k/, /æ/, /t/ is the target, the phonemes of the noun /h/, /æ/, /t/ and the verb /s/, /æ/, /t/ should be equally likely alternatives, as they have the same degree of phonological overlap with the target.

In contrast to this prediction, several studies have reported extremely high rates of syntactic category preservation (95% or above) in both normal (Abd-El-Jawad & Abu-Salim, 1987; del Viso et al., 1991; Fay & Cutler, 1977; Leuninger & Keller, 1994; Nootboom, 1969; Stemberger, 1985) and aphasic formal errors (Best, 1996; but see Blanken, 1998). Other studies have specifically compared the observed rate of syntactic category preservation to levels predicted by chance¹⁰. These studies have reported rates of syntactic category preservation significantly higher than predicted levels in both normal (Arnaud, 1999; Berg, 1992) and aphasic formal errors (Berg, 1992; Blanken, 1990; Dell et al., 1997; Gagnon et al., 1997; Martin et al., 1994).

A possible concern regarding these analyses stems from the fact that phonological neighbours of a word tend to share the word's syntactic category more than would be expected by a random pairing of words in the lexicon. Kelly (1992) reviewed evidence that this is in fact the case: in English, words within the same syntactic category tend to share many phonological features (e.g., stress, length, vowel quality). In addition, Kelly (1999) described simulation results that suggest that formal errors may be sensitive to the phonological structure of grammatical categories. Given these findings, chance rate of syntactic category preservation may vary with phonological distance from the target. If errors arise from disruptions to the production system that put the speaker at different distances from the target, then the calculation of chance rates of syntactic category preservation should, ideally, take phonological distance from the target into account.

In an analysis of the formal errors of an aphasic subject (CSS), Goldrick and Rapp (2000) attempted to address this issue. For each target/formal error pair in the subject's corpus, the analysis considered the syntactic category of all the words in the lexicon whose phonological overlap with the target was comparable to that of the error produced. For example, the patient produced "muffin" for the target "mitten". The analysis identified all those words in the lexicon whose overlap with "mitten" was comparable to that of "muffin" and tallied the number of them that were nouns. If the observed rates of grammatical category preservation were due solely to phonological proximity, the preservation rate observed in the errors should not have been significantly higher than

¹⁰ This has been estimated in several ways. One is by calculation of the long-term probabilities of randomly repairing targets and errors (Berg, 1992). The second involves pairing the targets with randomly selected words matched in CV shape with the formal error and with a frequency similar to that of the error (Blanken, 1990) or the target (Martin, Dell, Saffran, & Schwartz, 1994). The third examines the distribution of syntactic categories within the space of legal CVC sequences of English (Gagnon et al., 1997). The final method generates pseudo-errors by randomly pairing (correct) words drawn at random from target sentences in a speech error corpus (Arnaud, 1999).

that of the phonologically matched controls. This turned out not to be the case. We found a significant effect of grammatical category: 83% of CSS's (non-semantic) word errors shared grammatical category with their targets, significantly greater than the pooled chance estimate of 45%. This degree of syntactic category preservation in formal errors apparently contradicts the predictions of the discrete account.

Lexical frequency effects in formal errors. A number of studies have considered whether or not systematic lexical frequency effects are observed in the formal errors produced by intact and impaired subjects. As discussed earlier, there is no mechanism in the highly discrete system by which word level factors such as lexical frequency can influence the activation of *non-target* words. This is not to say that Stage 2 is generally insensitive to frequency under the discrete account: phoneme frequency might well influence phoneme selection (with more frequent phonemes being more likely to be mis-selected than less frequent ones) and the strength of the link between L-level nodes and phonemes may vary with frequency (such that more frequent words more strongly activate their phonemes). The point is that Stage 2 should be "blind" to the lexical properties of non-target words given that, during Stage 2, non-target L-level units (and, as a consequence, their connections to the phoneme level) are inactive.

Two types of analyses have been carried out to explore frequency biases in formal errors. Some studies have simply examined whether formal errors are significantly more frequent than their targets, as this would suggest a bias towards more frequent non-target outcomes. This result has been reported in a number of case studies of aphasic subjects (Blanken, 1990, 1998; Martin et al., 1994; but see Best, 1996).

A second, somewhat more sophisticated, analysis compares the frequency of formal errors with estimates of frequency values that would be expected by chance (in a system blind to the frequency of non-targets). Chance values have sometimes been calculated by generating all legal CVC strings of English and then calculating their mean frequency. When this was done, the average frequency of words in this "pseudocorpus" was found to be significantly lower than the average frequency of the formal errors in the actual error corpus (Gagnon et al., 1997; but see Best, 1996)—suggesting that the output system is sensitive to the lexical frequencies of formal neighbours of a target word and biased towards the more frequent formal neighbours.

These findings would be problematic for the discrete account, except that Nickels (1997) notes a potential difficulty with their interpretation. Nickels raises the possibility that the findings reflect a "regression to the mean". The reasoning is as follows: if it is *low frequency* target words that are especially susceptible to error (e.g., because of weaker links between L and phoneme level units), then errors (even if they are generated randomly) will tend, on average, to be more frequent than their targets. Similarly any randomly generated set of words will tend to be more frequent than the (generally low-frequency) target words that resulted in errors. This alternative explanation is plausible to the extent that errors are confined to relatively low-frequency target words. Consequently, until the possibility of regression towards the mean is taken into account, it is not clear that the reported data actually reflect a "true" lexical frequency bias for formal errors.

Phonological shape preservation in formal vs nonword errors. Some have argued that under the assumptions of the highly discrete account, formal errors ("muffin" for "mitten") and nonword errors ("mabben" for "mitten") should be comparable in the extent to which they preserve the target's phonological "shape" (e.g., phonemes in

certain positions, stress, syllable number, etc.) This is because, if something were to go wrong in the course of phonologically encoding the selected L-level node, there is nothing that should make the resulting nonwords more or less similar to the targets than the resulting formal errors. This prediction of the discrete account is seemingly contradicted by a number of reports indicating that nonword errors are more similar to target words than are formal errors (Best, 1996; Gagnon et al., 1997; Martin et al., 1994).

However, it is not clear that the discrete architecture necessarily predicts that formal and nonword errors should be comparable in their phonological similarity to the target words. The typical word has very few other *words* that are highly phonologically similar to it—it has few close formal neighbours. Therefore, if a small disruption were to occur in phonological encoding, the most likely outcome would be a nonword highly similar to the target. In order to make a formal error it would be necessary to have a larger disruption that would move the response further from the target and into a region of “phonological space” where there might be more formal neighbours. Although the more severe disruption would still be more likely to produce nonword vs word outcomes (and under more severe disruption outcomes overall would be less similar to the target), the probability of “landing on” a word that was nonetheless still phonologically similar to the target might well increase with increasing distance from the target. It is important to note that this would only occur in neighbourhoods in which the proportion of formal neighbours actually increases with distance from the target¹¹. This suggests that differences between formal and nonword errors in terms of phonological shape preservation may merely reflect differences in the distribution of error possibilities rather than being an indication of an interactive architecture (see Gagnon et al., 1997, and Nickels & Howard, 1995, for similar concerns).

Therefore, until analyses take into account the distributions of word and nonword opportunities for the target words, it is premature to conclude that the data on phonological shape preservation represent a problem for the discrete account.

Summary: Lexical effects on formal errors. Some of the data regarding lexical effects on formal errors are controversial. Frequency effects on formal errors could be attributed to “regression to the mean” and phonological shape preservation patterns have not accounted for distributional differences between word and nonword outcomes. The finding that is most robust is the strong tendency for *formal* errors to preserve the syntactic category of the target. This result is clearly problematic for the discrete position.

Proponents of a prearticulatory editor have claimed that syntactic category preservation in formal errors results from the same mechanism as the mixed error effect. That is, formal errors within the same syntactic category are similar to the target along two dimensions (form and grammatical category) and thus are more likely to be missed by the editor (Levelt et al., 1999). The shortcomings of the editor account that were raised earlier in the discussion of the mixed error effect apply here as well.

Lexical bias

A further consequence of Stage 2’s “blindness” to lexicality is that phonemes corresponding to words other than the target should be no more active than phonemes corresponding to matched nonwords. If the target is /k/, /æ/, /t/, then the nonword

¹¹ A systematic study of neighbourhood structure with regard to this dimension has not, to our knowledge, yet been undertaken.

outcome /l/, /æ/, /t/ should be no more or less likely than the outcome /s/, /æ/, /t/ (unless the phonemes themselves differ in frequency). However, some investigations have indicated that formal word errors are generated in excess of the rate predicted by discrete theories—this is termed *lexical bias*. Evidence of lexical bias effects has come primarily from two sources: from studies designed to elicit errors from intact subjects and from analyses of spontaneous error corpora that compare observed rates of word errors with chance rates.

Experimentally induced errors. Baars et al. (1975) introduced a procedure for inducing speech errors in normal subjects. They primed subjects to exchange the initial consonants of two words and found that subjects were more prone to onset exchanges when the exchange resulted in a word. For example, “darn bore” (where an exchange produces the word pair “barn door”) resulted in more errors than “dart board” (where an exchange produces the nonword pair “bart doard”). Subsequent studies (Dell, 1986, 1990) have replicated this result, providing support for the existence of a lexical bias effect.

Analyses of spontaneous errors. Because studies involving spontaneous speech error corpora often lack information regarding the number of opportunities for word and nonword errors (the corpora include only errors and not words attempted and successfully produced), analyses of these corpora typically establish chance rates for word errors by calculating the number of word errors that can be expected to result from the chance substitution of phonemes¹². Analyses of this sort have reported that observed rates of formal errors are greater than what would be expected by chance, providing evidence of lexical bias effects in normal subjects (Dell & Reich, 1981; Harley, 1984; Stemberger, 1985; but see del Viso et al., 1991; Garrett, 1976) as well as aphasics (Best, 1996; Gagnon et al., 1997; but see Nickels & Howard, 1995). These results are clearly problematic for the discrete position.

A number of researchers (e.g., Levelt, 1989) have questioned whether these results indicate that lexical bias effects necessarily arise internal to the phoneme retrieval process. They note that the experimentally induced lexical bias effect can vary with changes in instructions and experimental materials. On this basis they have claimed that lexical bias is not a consequence of the automatic process of phoneme retrieval, but is due instead to the operation of the post-lexical editorial process that is monitoring whether responses are words or not. In that situation, any non-target word response would have greater possibility of being missed by the editor than a nonword response. As before, we note the shortcomings of this account.

Summary of the challenges for the discrete approach

We have reviewed several lines of evidence that claim to contradict the predictions of the discrete account. Upon closer examination, some of the evidence (at least in its current form) does not present an insurmountable challenge to the discrete account: mixed error effects reported in experimental settings may be confounded by the influence of working memory; frequency effects on formal errors may reflect a “regression to the mean” and differences in formal and nonword errors with respect

¹²This is estimated either through calculation of long-term probabilities of errors resulting in words (e.g., Dell & Reich, 1981) or through Monte Carlo generation of errors (e.g., Best, 1996).

to their phonological similarity to the target may reflect the properties of phonological neighbourhoods.

But not all the evidence suffers under close scrutiny. There are various robust findings that remain problematic for the discrete account¹³:

- *The mixed error effect.* Under the discrete account, the rate of mixed errors should reflect the sum of two independent error processes: some semantic errors should, by chance, be phonologically related to the target; and some phonological errors should, by chance, be semantically related to the target. The strongest evidence in this regard comes from several studies of spontaneous speech errors with normal and aphasic subjects (Blanken, 1998; Dell & Reich, 1981; Dell et al., 1997; Harley, 1984; Martin et al., 1996; Rapp & Goldrick, 2000) that have found that mixed errors occur at rates significantly greater than the predicted rate.

- *Syntactic category effects.* Under the discrete account, all syntactic processing is complete prior to Stage 2. Given this, and as phonological errors arise only during Stage 2, phonologically based errors should not exhibit a bias to preserve the target's syntactic category. Nonetheless, many studies (Abd-El-Jawad & Abu-Salim, 1987; Arnaud, 1999; Berg, 1992; Best, 1996; Blanken, 1990; Dell et al., 1997; del Viso et al., 1991; Fay & Cutler, 1977; Gagnon et al., 1997; Goldrick & Rapp, 2000; Leuninger & Keller, 1994; Martin et al., 1994; Nootboom, 1969; Stemberger, 1985) have shown strong syntactic category preservation effects for formal errors.

- *Lexical bias.* Under the discrete account, lexical outcomes should not be favoured over non-lexical outcomes during Stage 2 processing. Given this, and as phonological errors arise during this stage, the discrete account predicts that lexical outcomes should occur at chance level rates for errors that are phonologically similar to the target words. In apparent contradiction with this prediction, several studies (Best, 1996; Baars et al. 1975; Dell 1986, 1990; Dell & Reich, 1981; Gagnon et al., 1997; Harley, 1984; Stemberger, 1985) have reported a clear lexical bias in both normal and aphasic speech.

We now turn to examine the highly interactive account. We first describe the basic assumptions of the account and then we consider the empirical challenges that it faces.

A HIGHLY INTERACTIVE ACCOUNT

Mechanisms of interaction

The highly interactive account proposed by Dell et al. (1997) incorporates two mechanisms to create interaction between the semantic and phonological processes: *cascading activation* and *feedback*. In a system with cascading activation, there is no restriction on the forward flow of activity in the network: once a unit is activated, it sends activity forward to any units with which it is connected. The addition of feedback connections allows a unit to send activation back to any units connected to it at a prior level. As we will show, feedback allows for phonologically based processing to influence the outcome of Stage 1, while cascading activation allows for semantically based processing to influence the outcome of Stage 2.

¹³Levitt et al. (1999) suggest (p. 35) that occasionally two L-level entries are selected instead of only one. They argue that this situation could form the basis of both the mixed error and syntactic category preservation effects. It strikes us that this is, presumably, a rather rare occasion and therefore unlikely to account for these robust and (especially in the case of syntactic category preservation) large effects.

We can more concretely consider the consequences of incorporating cascading activation and feedback into the generic architecture by walking through the major events occurring during Stage 1 and 2 processing of the target CAT.

Stage 1: Processing begins with the activation of the semantic features associated with a lexical concept (e.g., [feline, pet] for <CAT>). Activation from these features spreads to the L-level and syntactic features, where it activates the target and its semantic and syntactic neighbours (e.g., DOG, RAT).

Activation cascades on to the phoneme units, allowing for the phonemes of the target as well as those of its semantic and syntactic neighbours to become active. For example, in Figure 4 the phonemes for /g/ and /t/ (connected to DOG and RAT, respectively) become active during Stage 1. This is in marked contrast with the discrete system (see Figure 3).

Due to the presence of feedback connections, feed-forward activation from semantics is not the sole contributor to L-level processing. The phoneme units feed back onto the L-level units, and these, in turn, feed back onto the semantic level (as shown in Figure 4). Thus, the phonemes /k/, /æ/, and /t/ send activation back on to the L-level, causing the formal neighbours RAT and SAT to become active. This is, again, in striking contrast with the highly discrete systems (or even systems with only cascading activation) where formal neighbours are not active at the L-level. In this way, phonological information can influence L-level selection. Furthermore, through feedback from the L-level to the semantic level, phonological processing can also exert an influence at the semantic level.

Stage 1 ends with the selection of the most active L-level unit. If all goes well, this should be CAT, but the competitors will include both semantic and formal neighbours. The selection process has the effect of enhancing the activity of the selected L-level unit relative to its competitors.

Stage 2: As the selected L-level unit's activity is much greater than that of its competitors, it dominates subsequent Stage 2 processing. However, in contrast to the

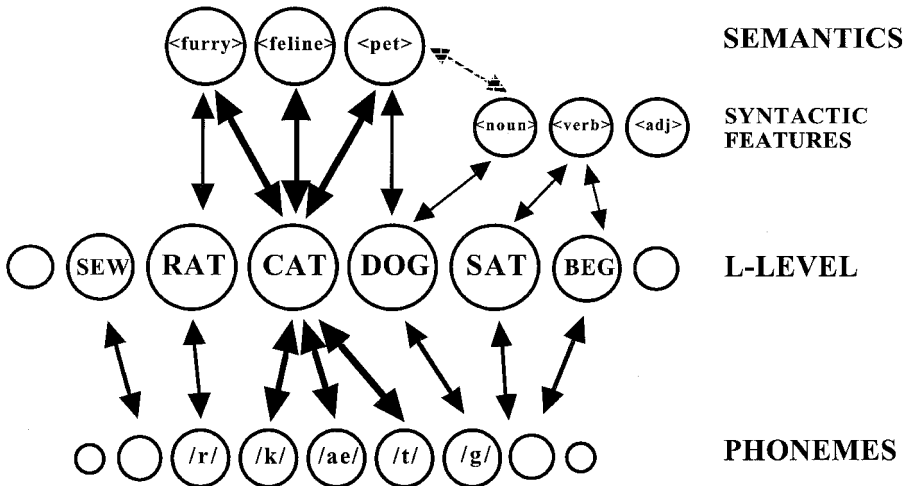


Figure 4. The highly interactive account. Thick arrows denote activation flow involving the target; thin arrows denote activation flow involving its lexical neighbours.

discrete theory, all other active L-level units continue to pass on their activity. This allows for the continued influence of semantically based processing during Stage 2. Thus, if an error occurs during Stage 2, the phonemes of semantic and syntactic competitors such as DOG or RAT will compete with the target phonemes (Figure 4). In addition, activation continues to feed back from the phoneme units to the L-level units, allowing L-level units of formal neighbours of the target (SAT and HAT) to significantly shape Stage 2 processing. Activation also continues to feed back to the semantic level. Stage 2 ends with the selection of the most active phoneme units.

Challenges for the highly interactive account

By incorporating cascading activation and feedback, the highly interactive position can account for all of those findings that we identified as being problematic for the highly discrete account: mixed error, syntactic category, and lexical bias effects. At this point we will not specifically discuss how it is that cascading activation and feedback accomplish this, although this will become apparent from the following discussion (for reviews, see Dell et al., 1997; Rapp & Goldrick, 2000). Instead, we will focus the discussion on those findings that are problematic for the highly interactive account. We will be specifically concerned with the fact that under the highly interactive account, cascading activation and feedback provide a mechanism by which phonological information can be expected to influence events at both the L and semantic levels. We first evaluate evidence for phonological effects at the L-level and then turn to evidence regarding phonological effects at the semantic level. In this discussion we review two case studies previously reported in Rapp and Goldrick (2000).

Phonological effects and the L-level

Under a highly interactive account, the considerable feedback from the phoneme level back to the L-level creates a situation in which semantic errors arising at the L-level can be influenced by phonology. This provides the basis for a mixed error effect in L-level selection. This occurs in the following way: cascading activation from the target (CAT) will activate its phonemes (/k/, /æ/, /t/) during Stage 1 processing. Feedback from these phonemes allows mixed neighbours (RAT) to be more active at the L-level than either semantic (DOG) or format (SAT) neighbours.

Furthermore, the feedback creates a situation in which formal neighbours are active at the L-level. Feedback from the target's phonemes (/k/, /æ/, /t/) will activate formal neighbours of the target (e.g., HAT, SAT). This is in contrast to the highly discrete theory, where such neighbours are inactive (or, at best, only coincidentally receive activation from syntactic features).

Given this, a highly interactive account predicts that failures at the L-level should: (1) produce a mixed error effect; and (2) give rise to formal errors. To evaluate these predictions, we review evidence from the performance of an aphasic subject, PW, who suffered from an impairment that can be localised to the L-level (Rapp & Goldrick, 2000).

Localisation of PW's deficit. PW was a 51-year-old right-handed man who had completed one semester of education at the university level. He was employed as a manager of a meat department when he suffered a left hemisphere stroke 24 months prior to the onset of testing (see Rapp, Benzing, & Caramazza, 1997, and Rapp & Caramazza, 1998, for further details).

PW's spoken output contained a large number of semantic errors. However, PW's comprehension performance suggests that the semantic errors in single word production are not attributable to a semantic deficit. This conclusion is supported by his performance on three types of tasks: (1) drawing items named by the experimenter; (2) word-picture verification; and (3) spoken and written naming on single trials.

For the drawing task, PW was asked to draw 260 items from the Snodgrass and Vanderwart (1980) picture set. He produced three clear errors (99% correct). Two word-picture verification tasks were also administered. In the first, PW was shown each of the 260 Snodgrass and Vanderwart pictures on three different occasions auditorily accompanied by either: the correct name; a semantically related word; or a phonologically related word. Each time, he was asked to indicate (yes/no) if the picture and word matched. He was 95% correct (741/780), with most of the errors occurring with semantically related words. His performance is just below that of controls (range: 96–100% correct). A similar verification task was administered both auditorily and visually with a different picture set; his performance was similar on both tasks: auditory presentation: 93% correct (134/144); visual presentation: 95% correct (137/144). Overall, his high level of accuracy on these tasks suggests that his semantic processing is largely intact.

Further evidence of intact semantic processing comes from several tasks where PW was asked on each trial to produce both spoken and written responses to pictures (one after the other, in both orders). On many of these trials, he produced semantic errors in spoken production while producing the correct written response (e.g. picture of a tiger → 'lion'; T-I-G-E-R; Rapp et al., 1997). Furthermore, he typically recognised that he had made the spoken error as soon as it was produced and he would either try again to name it (typically unsuccessfully) or provide a definition of the target word. This pattern suggests that his semantic errors in spoken production did not arise from a semantic impairment. If the spoken errors had arisen at the semantic level—common to both speaking and writing—errors in one modality would have been accompanied (on the same trial) by errors in the other.

To help localise the production deficit within post-semantic processes, PW was administered 258 items from the Snodgrass and Vanderwart (1980) picture set for both spoken naming and repetition. Table 1 shows his performance on these tasks. There are two noteworthy aspects: his excellent repetition performance and the absence of phonological errors in his spoken picture naming. Both of these indicate that both input and output phonological processing were largely intact. Having eliminated the semantic and phoneme levels as loci for his naming impairment, we can conclude that it is highly likely that PW suffered from an L-level deficit.

TABLE 1
Percent correct in naming and repetition for PW on the Snodgrass & Vanderwart (1980) picture set

	<i>Correct</i>	<i>Semantic</i>	<i>Similar word</i>	<i>Nonword</i>	<i>Unrelated word</i>	<i>Don't know</i>
Oral pix naming	72.1	19.0	0	0	3.1	5.8
Repetition	99.6	0	0.4	0	0	0

Semantically unrelated words were scored as 'similar' if they shared at least 50% of the target's phonemes; otherwise they were 'unrelated'.

We are now in a position to evaluate the prediction of the highly interactive account that mixed and formal errors should arise subsequent to an L-level deficit.

Mixed error effects. On average, PW's semantic errors shared 22% of the phonology of the target. Is this degree of overlap greater than expected by the highly discrete account?

To determine the chance rate expected by the highly discrete account, we used a Monte Carlo method to estimate the average amount of phonological overlap that would result from a random pairing of words from the eight semantic categories that PW's errors came from. First, 239 target/error pairs (drawn from the corpora of three subjects) were randomly re-paired. Second, a mean phonological overlap was calculated for this random pairing. The re-pairing procedure was repeated 5000 times to yield a distribution of average phonological overlap values produced by chance. Average phonological overlap values as large as PW's (22%) were never observed in these 5000 random pairings of words (mean phonological overlap of the 5000 random pairings: 12.9%; standard deviation 1%; range 9.7–16.9%).

Note that unlike the mixed error analyses reviewed earlier, we do not have to correct for errors that may have arisen during Stage 2. This is because we were able to localise PW's deficit to the L-level and to exclude the phoneme level as a significant error source. One problem with the analysis, however, is that it does not take into account the fact that virtually all of PW's errors are within-category semantic errors (e.g., "lion" for <TIGER> but not "fierce" for <TIGER>). If items from the same semantic category are more phonologically similar to one another than to items from different categories, then we would have overestimated the size of PW's mixed error effect. This problem can be addressed by applying a correction for within-category similarity.

We determined this correction by calculating the mean phonological overlap of words within the eight semantic categories that PW's errors came from, as well as the mean overlap across these categories. We found that, on average, the phonological overlap of words within a semantic category is 2.7% greater than across semantic categories. We therefore adjusted PW's overlap measure to account for this within-category phonological overlap advantage, yielding an adjusted mean phonological overlap that was still well outside the chance range. Thus, a significant mixed error effect is indeed found at the L-level, consistent with the first of the two predictions of the highly interactive account.

Formal errors. As indicated earlier, the highly interactive account predicts that formal errors should arise from damage at the L-level. PW's performance did not match this prediction—he made no formal errors (and no nonword errors), even though his accuracy level was below 75%.

In sum, the highly interactive account correctly predicts the presence of a mixed error effect following L-level damage, but incorrectly predicts the presence of formal errors. On the one hand, PW's performance supports the notion of feedback from the phoneme level to the L-levels; on the other hand, the absence of formal errors in his performance suggests that this feedback cannot be strong enough to make formal neighbours effective competitors.

Phonological effects at the semantic level

The highly interactive account assumes feedback not only from the phoneme level to the L-level but also from the L-level to semantics. If this feedback is sufficiently strong, activation from the phonemes will spread to the L-level and then be transmitted to the

semantic level—thus providing another source for the mixed error effect. In addition, if the feedback is sufficiently strong, formal neighbours will become active at the semantic level and should also be produced as errors. To evaluate these predictions, we examine the performance of an individual who suffered from damage to the semantic level (Rapp & Goldrick, 2000).

Localisation of deficit. KE was a right-handed man who was 52 years old at the time of testing. He had an MBA degree and had worked as a high-level manager in a large corporation prior to a thromboembolic stroke 6 months prior to testing (see Hillis, Rapp, Romani, & Caramazza, 1990, for a detailed report).

KE's performance was within normal range on tests of visual perception, reasoning, and arithmetic skills. His spoken repetition was also intact. In contrast, he was markedly impaired on tasks involving lexical semantics. This is shown in Table 2.

There are two striking aspects of KE's performance. First (like PW), KE produced no phonologically related responses in spoken output—all of his errors were semantic or "don't know" responses. This pattern rules out a phonological locus of impairment, as a deficit at that level should have resulted in at least some phonological errors. This is further supported by KE's error-free performance on repetition tasks.

Second, there is the remarkable similarity of KE's performance across a wide range of lexical tasks. KE produced similar rates of semantic errors regardless of the input modality (written, spoken, picture, tactile) or output modality (written and spoken) in which he was tested. This pattern indicates a common error source in all of the tasks. Given that the tasks all share lexical semantic processing, the semantic level would seem to be the most likely deficit locus. The alternative of multiple impairments to different input/output mechanisms was rejected by Hillis et al. (1990) on the basis of item consistency analyses.

TABLE 2
Percent correct across a range of lexical tasks for KE

<i>Task</i>	<i>Correct</i>	<i>Semantic</i>	<i>Formal</i>	<i>Nonword</i>	<i>Unrelated word</i>	<i>"Don't know"</i>
Oral pix naming	55.5 n=335	37.6	0	.3	.3	6.2
Written pix naming	55.2 n=335	31.9	.3	6.6 ^a	.9 ^b	5.1
Oral reading	57.6 n=335	34.6	.6	0	.3 ^b	6.9
Writing to dictation	58.5 n=335	25.1	.6	9.9 ^a	2.1	3.9
Oral tactile naming	53.2 n=47	44.7	0	0	0	2.1
Written tactile naming	59.6 n=47	34.0	0	2.1	0	4.2
Auditory comprehension	58.1 n=191	40.3	0	n/a	1.6 ^c	0
Reading comprehension	64.9 n=191	28.3	.5	n/a	6.8 ^c	0

^aIncludes misspelled, possible semantic errors (e.g., crab → [clam] → clim).

^bIncludes possible visual → semantic errors (waist → [wrist] → watch) and semantic → visual errors (cheek → [rouge] → rug).

^cRejection of correct word/picture matches.

Mixed error effects. The highly interactive account predicts a mixed error effect for KE's semantic errors. However the results of an analysis just like the one described earlier for PW, revealed that this was not the case. On average, KE's semantic errors in picture naming shared 12.4% of the target's phonology (corrected for within-semantic-category overlap). Out of the 5000 random target-error pairings, phonological overlap equal to or greater than this was observed 3611 times ($p > .72$).

Formal errors. In highly interactive systems, formal neighbours should become activated at the semantic level and, at least occasionally, be produced as errors. Even though KE's accuracy rate was below 60%, he did not produce any formal errors. This is further evidence that, contrary to the predictions of a highly interactive account, there is very little influence of phonology on processing at the semantic level.

Summary of the challenges for the highly interactive account

The highly interactive theory can account for the mixed error effect and syntactic category bias that the highly discrete account cannot account for (Dell et al., 1997). On those grounds, therefore, it would appear that a high degree of interaction is supported by the empirical results. However, the data reviewed here demonstrate that assuming a high degree of interaction also makes some incorrect predictions. In particular, a highly interactive account predicts that phonological effects should be present at all levels of the production system (Nickels, 1995)¹⁴. KE's data, with the absence of phonological effects (mixed error effect or formal errors) at the semantic level, suggest that either there is no feedback from the L-level to the semantic level or that it is so minimal that it is "functionally invisible" (see Rapp & Goldrick, 2000, for simulation results supporting this conclusion, as well as Harley & MacAndrew, 1995). In addition, PW's data indicate that there must be important restrictions on phoneme level to L-level feedback. Although functional feedback is required to explain PW's highly significant mixed error effect¹⁵, the absence of formal errors indicates that the feedback from phoneme level to L-level must be restricted. We further explore these restrictions on interactivity in our discussion of RIA.

THE RESTRICTED INTERACTION ACCOUNT (RIA)

The highly discrete position incorrectly predicts that semantic and phonologically based processing should never interact. In contrast, the highly interactive position allows for too much interaction, yielding predictions that are not matched by data from PW and KE. In response to these challenges Rapp and Goldrick (2000) proposed an account that allows for interaction, but restricts it: the restricted interaction account (RIA). Specifically, RIA incorporates interaction by including: (1) cascading activation and (2) feedback from the phoneme level to the L-level. RIA also retains considerable discreteness by, among other

¹⁴Note that this is not a claim made by *all* architectures that incorporate interactivity. We are examining the predictions of theories that posit significant amounts of interaction between phonemes and semantics. Theories that have interaction but restrict it through one or more mechanisms might not make this prediction (see the later discussion of RIA, and Harley, 1995).

¹⁵The need for such feedback to account for mixed errors arising at the L-level provides crucial evidence against purely cascading theories (Rapp & Goldrick, 2000).

things, excluding feedback from the L-level to the semantic level¹⁶. We argue that this proposal (depicted in Figure 5) can account for the full range of findings that we have been considering.

Processing assumptions of RIA

Stage 1: Processing begins with the activation of the semantic features associated with a lexical concept. Activation from these features spreads to the L-level and the syntactic features, where the target and its syntactic and semantic neighbours are activated.

In contrast to the discrete theory (but as in the highly interactive account) activation is also passed on to the phoneme units, allowing for the phonemes of the target and its semantic neighbours to become active. In addition, the phoneme units feed back to the L-level units, activating formally related neighbours of the target. This allows phonologically based processing to influence the outcome of Stage 1. However, in contrast to the highly interactive architecture, this activation does *not* feed back onto the semantic level (see Figure 5).

Stage 1 ends in the selection of the most active L-level unit. As in the other accounts, the selection process enhances the activity of the selected L-level unit relative to its competitors.

Stage 2: As the selected L-level unit is much more active than its competitors, it dominates subsequent Stage 2 processing. However, in contrast to the discrete theory, the other L-level units are also allowed to pass on their activity to the phoneme level. Furthermore, activation also continues to feed back from the phoneme units to the L-level

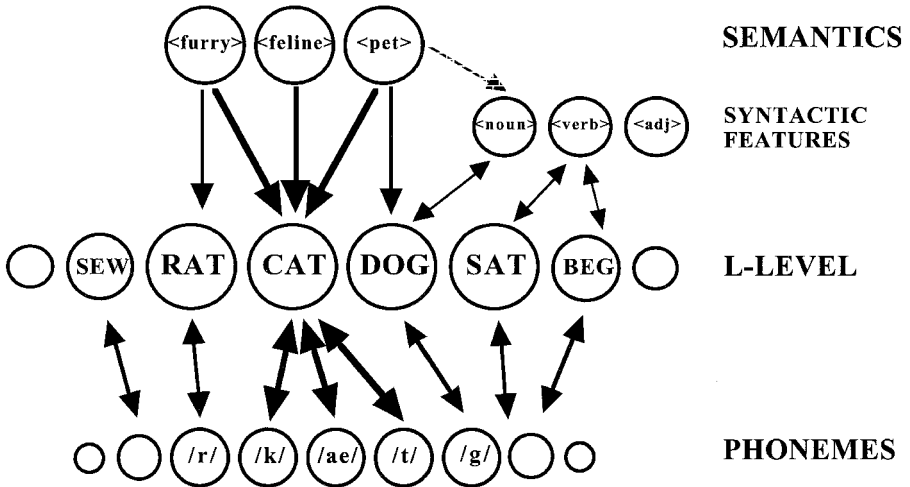


Figure 5. The restricted interaction account (RIA). Thick arrows denote activation flow involving the target; thin arrows denote activation flow involving its lexical neighbours.

¹⁶Harley and MacAndrew (1995) also propose that feedback is absent between lexical and semantic representations. Unlike RIA, however, their proposal does not specifically restrict the strength of feedback from phonological to lexical representations (see Rapp & Goldrick, 2000, for discussion on the restrictions on phoneme level to L-level feedback).

units. This allows semantic and syntactic competitors to influence Stage 2 processing. Stage 2 ends with the selection of the most active phoneme units.

Simulation

We constructed a computer simulation in order to assist us in evaluating RIA. We simulated the naming of a single CVC target word (such as CAT) from an “average” English neighbourhood (the characteristics of an average English neighbourhood are based on the work of Dell et al., 1997). This neighbourhood consisted of 29 words (including the target). There were three semantic neighbours of the target; one of these was a mixed error (sharing two phonemes with the target). Of the remaining words, 11 were phonologically similar to the target, and the other 14 were unrelated both semantically and phonologically to the target.

This neighbourhood was implemented in a network with the representational characteristics of the generic two-stage framework. The main difference was that the simulation included an additional conceptual level that included one concept node for each of the 29 words (prior to the semantic level), representing the conceptual preparation processes that serve to activate the semantic features of the semantic level. In the simulation, Stage 1 processing began with activation of the semantic feature units; after a fixed number of processing cycles, the most highly active L-level unit was “selected” by setting its activation to a high level of activation. Following this selection, Stage 2 processing occurred for a fixed number of processing cycles, followed by selection of the most active onset, vowel, and coda units as the network’s output.

Unless stated otherwise, damage to the naming process was simulated by adding noise to units at one or more levels (e.g., L-level damage was simulated by adding noise to the L-level units) and results and statistics are based on 10,000 simulated naming attempts. Further details of the implementation can be found in Rapp and Goldrick (2000).

We first discuss how RIA can account for the data that we discussed as being problematic for the highly interactive account; we then consider more recent challenges that have been posed to interactive accounts.

Accounting for the challenges to the highly interactive position

In this section we show that RIA can: (1) match the pattern of mixed errors + no formal errors exhibited by PW subsequent to L-level damage, and (2) account for KE’s absence of both formal errors and a mixed error effect. In effect, we show that RIA does not suffer from the shortcomings of either the discrete or the highly interactive accounts.

Phonological effects at the L-level under RIA

The phoneme level to L-level feedback in RIA allows for the possibility of a mixed error effect subsequent to L-level damage. Because of the feedback, mixed L-level neighbours of a target such as CAT (e.g., RAT) receive both top-down activation from the semantic features and bottom-up activation from the phonemes they share with CAT. This gives them an advantage over both semantic neighbours (e.g., DOG) that receive only semantically based activation, and formal neighbours (e.g., SAT) that receive only phonologically based activation. At the same time, however, feedback between phoneme and L-levels must be limited to prevent formal neighbours from becoming strong competitors at the L-level and appearing as errors subsequent to L-level damage.

To determine if a true mixed error effect can be obtained under RIA in the absence of formal errors (PW's pattern), we simulated damage at the L-level and compared the simulated rate of mixed errors to the rate predicted for the simulated neighbourhood by the discrete account. In the simulation neighbourhood that we used, there were twice as many purely semantic (i.e. phonologically unrelated) neighbours of the target as mixed neighbours. Given that in the absence of feedback, all semantic errors are equally likely at the L-level, the highly discrete account predicts that the rate of mixed errors should be $\frac{1}{2}$ the rate of purely semantic errors. In contrast to this prediction, the observed rate of mixed errors in the damaged RIA simulation was significantly greater than $\frac{1}{2}$ the rate of purely semantic errors (see Figure 6A; Z scores ranged from 13.8 to 27.16 at various levels of damage).

Furthermore, at PW's accuracy level, fewer than 1% of the errors were non-semantic. This is shown in Figure 6A. Thus, the simulation work demonstrates that it is possible to restrict feedback enough to avoid formal errors while still generating a mixed error effect (see Rapp & Goldrick, 2000, for further discussion on limitations on the strength of feedback).

Phonological effects at the semantic level under RIA

By now allowing feedback from the L-level, RIA prevents phonological effects from arising at the semantic level. At this level, mixed neighbours (<RAT>) receive only semantically based activation. This should produce the same outcome under damage as expected by the highly discrete account. As all semantic neighbours are equally likely to be selected (regardless of phonological similarity to the target), there can be no mixed error effect at the semantic level in RIA. In fact, simulation results, shown in Figure 6B, confirm the absence of mixed error effects following damage to semantic processes¹⁷.

Under RIA, at the semantic level formal neighbours of the target (e.g., <SAT>) receive no activation (despite being active at the L-level). This renders them essentially inactive, and makes them extremely unlikely error outcomes. This is demonstrated in Figure 6B where it can be seen that only semantic errors were produced following damage to semantic processes.

In sum, RIA can account for the findings that were problematic for the highly interactive account. By restricting interactivity, it prevents formal neighbours from being significant competitors at the L-level, and precludes phonological effects at the semantic level.

Accounting for the challenges to the highly discrete account

We identified three fairly robust empirical effects that the highly discrete account could not explain: the mixed error effect, syntactic category preservation with formal errors, and lexical bias. Here we discuss how RIA accounts for these three effects.

The mixed error effect under RIA

As shown earlier, RIA allows for a mixed error effect following L-level damage. Interestingly, it should also allow for a mixed error effect following damage to the phoneme level. Because of cascading activation both prior to and following L-level

¹⁷In order to restrict damage to semantic processing, KE's deficit was simulated by damaging the concept layer. This layer of units represents conceptual preparation processes that activate semantic features (see earlier and Rapp & Goldrick, 2000, for details).

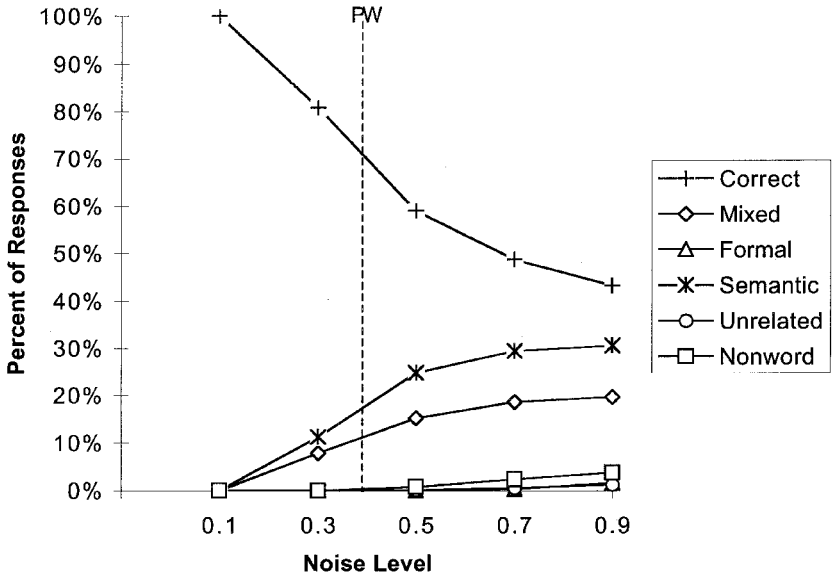
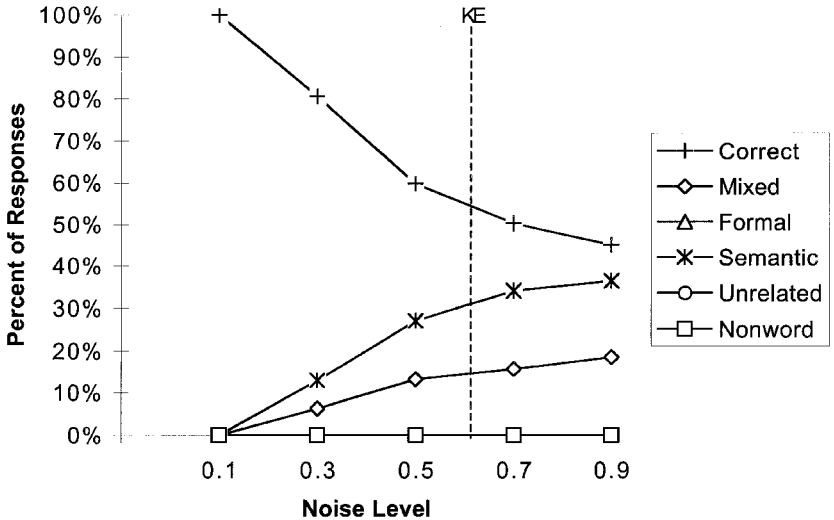
A**B**

Figure 6. Simulation results showing RIA's ability to account for the data that represent a challenge to the highly interactive account. (A) Results of 10,000 runs with damage to the L-level at various noise levels. PW's accuracy level is indicated by a dashed line. (B) Results of 10,000 runs with damage to semantic processing at various noise levels. KE's accuracy level is indicated by a dashed line.

selection, semantic neighbours activate their phonemes. Because of this, the response “rat” will be favoured over “hat” or “dog”. This occurs because all of the phonemes of “rat”—/r/, /æ/ and /t/—will receive activation because of their semantic overlap with the target CAT and, in addition, the subset /æ/ and /t/ will receive additional activation from the phonological encoding of the target CAT. In contrast, only the /æ/ and /t/ of “hat” will be activated from the phonological encoding of “cat”, and the phonemes of “dog” receive activation only as a result of their semantic overlap with the target.

In the simulation, we examined if a mixed error effect could indeed arise at the phoneme level by comparing the observed rate of mixed errors subsequent to phoneme level damage to the rate predicted by the discrete account. In the simulation neighbourhood, we selected a word such as /s/, /æ/, /t/ (formal*) that was matched with the mixed error in terms of phonological overlap with the target phonemes (e.g., /r/, /æ/, /t/). As the two outcomes were matched for phonological overlap with the target, the highly discrete account predicts that formal* errors should occur just as frequently as mixed errors. In contrast to this prediction, however, damage to the phoneme level in the simulation yielded significantly more mixed errors than formal* errors (at various levels of phoneme level damage with Z scores ranging from 13.81 to 27.16).

In sum, in contrast to the discrete account, RIA allows for a mixed error effect to arise from either L or phoneme level damage.

Syntactic category bias in formal errors

Under IRA formal neighbours are poor competitors at the L-level because of relatively weak phoneme to L-level feedback. As a result, syntactic category preservation in formal errors cannot be readily attributed to failures of L-level selection. However, cascading activation allows for syntactic category preservation effects with formal errors to arise at the phoneme level. This occurs because L-level units sharing the target’s syntactic category (e.g., target: CAT/syntactic neighbour: LEG) receive top-down activation from the target’s syntactic features, boosting their activation over units that do not share the target’s syntactic category (e.g., BEG). This activation advantage can then be passed on to the phoneme level so that the phonemes of LEG will be more active than the phonemes of BEG.

In the simulation, we compared the observed rate of formal syntactic neighbour¹⁸ outcomes with those of a matched formal neighbour—formal** (that shared neither semantic nor syntactic features with the target) (e.g., /m/, /æ/, /t/ vs. /s/, /æ/, /t/). As the two outcomes are matched for formal similarity with the target, the highly discrete account predicts that formal** and the syntactic neighbour should occur with equal frequency. In the RIA simulation, however, the phonemes of syntactic neighbours were selected significantly more often than the phonemes of formal** (at various levels of damage, Z scores ranged from 10.68 to 26.75).

¹⁸In our previous simulation work (Rapp & Goldrick, 2000) we did not include a representational level with syntactic features. Therefore, to examine this specific phenomenon with the simulation, we altered the neighbourhood of the simulation so that the mixed neighbour now shared syntactic category (and not semantic information) with the target. Three units in the simulation (previously semantic units) were selected to be syntactic feature units; these were connected to the syntactic (formerly mixed) neighbour as well as the target.

Lexical bias under RIA

Dell (1986) argued that lexical bias in a highly interactive system results from the presence of feedback connections from the phonemes to the lexical units (L-level units in the generic architecture). For example, suppose the target word CAT is selected at the L-level. It will pass activation on to its constituent phonemes (/k/, /æ/, /t/). These units will then pass activation back to *all* L-level units that share phonemes with the target (e.g., HAT, RAT, BAT, etc.). These, in turn, will activate *all* of their constituent phonemes—including those not related to the target (e.g., HAT will activate /h/). These unrelated phonemes will then feed back onto their L-level nodes, setting up what Dell referred to as “positive feedback loops”. These loops will systematically favour particular sets of phonemes that correspond to words. Nonword outcomes (e.g., /l/, /æ/, /t/), lacking an L-level unit to tie them together and create a positive feedback loop, will not receive this benefit. Hence the system will be biased towards lexical outcomes.

Given that RIA assumes feedback connections between the phonemes and the L-level, it too allows for the creation of these loops. This was confirmed by comparing, in the simulation, the rate of matched word and nonword responses following phoneme level damage. As the two outcomes are matched in phonological similarity to the target, the discrete account predicts that the two outcomes should occur at equal rates. In the simulation, however, word outcomes were more likely than nonword outcomes, producing the desired lexical bias effect ($Z = 2.82$).

Summary of the RIA proposal

RIA is not highly interactive because it does not allow feedback from the L-level to the semantic level, and because it restricts the strength of feedback from the phoneme to the L-level. Neither is it highly discrete, as it allows for cascading activation and limited feedback. By selectively incorporating interactivity, RIA can account for data that are problematic for more extreme positions on the discreteness/interactivity continuum.

CHALLENGES FOR RIA

Recently, additional challenges to interactive theories have been put forward. One challenge involves the reports of aphasic individuals who make only phonological (no semantic) errors in naming. Another is the finding that certain aphasic subjects produce greater numbers of formal than nonword errors. Here we consider the extent to which these findings are problematic for RIA.

Only phonological errors in naming

In systems with cascading activation (with or without feedback), significant disruption to any of the three levels should result in at least some semantic errors. This is because in either discrete and interactive systems, semantic neighbours are, of course, very strong competitors at the semantic and L-levels; cascading activation provides support for semantic neighbours at the phoneme level as well. Thus, interactive theories would appear to predict that all aphasics should produce at least some semantic errors in naming. Indeed, simulations of highly interactive theories support this prediction (Dell et al., 1997; Rapp & Goldrick, 2000). However, as pointed out by Foygel and Dell (2000) several case studies (e.g., Caplan, Vanier, & Baker, 1986; Caplan & Waters, 1995; Caramazza, Papagno, & Ruml, 2000; Goldrick, Rapp, & Smolensky, 1999; Hillis, Boatman, Hart, & Gordon, 1999; Wilshire & McCarthy, 1996) describe individuals who

make only phonologically related word and nonword errors in naming. This pattern, therefore, would seem to constitute a challenge for theories such as RIA.

Post-lexical phonological processing

We would argue that the pattern of only phonological errors can be explained by damage to *post-lexical phonological processing* that occurs subsequent to the processing stages we have been concerned with thus far. Goldrick et al. (1999) proposed a post-lexical phonological process that takes as input the phonemes selected at the end of Stage 2 and, from them, generates a detailed phonological representation that is used to drive articulatory processing. This proposal is based on an often-made distinction between processes that *retrieve* stored phonological information and processes that “*fill-in*” and elaborate the stored information (e.g., Béland, Caplan, & Nespoulous, 1990; Béland & Favreau, 1991; Butterworth, 1992; Caplan, 1987; Garrett, 1982, 1984; Kohn & Smith, 1994; Levelt et al., 1999).

To account for the pattern of only phonological errors in naming, we assume that post-lexical phonological processing operates solely on the items *selected* at the phoneme level (much as Stage 2 in the highly discrete account operates only on L-level items selected during Stage 1). That is, we assume that activation does not cascade from the phoneme level to the post-lexical phonological level. Given this, errors during post-lexical phonological processing should be influenced solely by phonological factors, and not by semantic or lexical information.

In order for such a proposal to be more than merely an ad hoc explanation of the “phonological-errors-only pattern”, deficits arising from damage to the phoneme versus post-lexical phonological processing levels should differ in more ways than simply with regard to the presence or absence of semantic errors. Recent work suggests that this is indeed the case.

On the basis of contrasting patterns of accuracy on naming and repetition tasks (without considering error types), Goldrick et al. (1999) proposed distinct phoneme level and post-lexical deficit loci for two individuals. Specifically, the pattern of impaired naming accompanied by intact repetition was attributed to a lexical deficit locus, while the pattern of impaired naming and impaired repetition was ascribed a post-lexical deficit locus. Importantly, subsequent error analyses revealed that the error characteristics were markedly discrepant in ways that are consistent with the different deficit loci.

Goldrick et al. (1999) found that the subject with the phoneme level deficit produced both semantic and phonological errors and exhibited significant effects of lexical frequency (high frequency words named better than low). However, this subject did not demonstrate sensitivity to phonological variables such as syllable position. In contrast, the subject with the hypothesised post-lexical phonological processing deficit produced only phonological errors and exhibited no lexical frequency effect. In addition, her naming performance was sensitive to a number of phonological variables.

An example of the differential sensitivity to syllable position is presented in Table 3. Only phonological errors (words and nonwords) were included in the analysis. As indicated in Table 3, phoneme accuracy for the subject with a phoneme level deficit was not influenced by syllable position: his error rate for onsets was not significantly different from that of codas, $\chi^2(1, N = 3651) = 1.44, p > .05$. In contrast, the subject with a post-lexical phonological processing deficit was significantly more impaired on codas than onsets, $\chi^2(1, N = 2111) = 37.43, p < .05$. Thus, even though both subjects produced

TABLE 3
 Percentage of substitutions and deletions of segments in
 one- and two-syllable words according to syllable position

% Error	CSS (phoneme level deficit)	BON (post-lexical phonological processing deficit)
Onset	1.7	2.5
Coda	2.3	8.7

phonological errors, their errors differed in ways that support a distinction between lexical phonological and post-lexical phonological processing. The results suggest that post-lexical phonological processing is sensitive to the phonological environment of segments, whereas processes at the phoneme level treat all segments similarly, regardless of syllabic position.

In sum, while it is true that damage to any of the three levels of the generic framework should produce semantic errors, the pattern of only phonological errors in naming is not necessarily problematic for RIA. We assume that this pattern arises as a result of damage that occurs post-lexically. In support of this proposal, we have briefly reviewed independent evidence for the distinction between lexical phonological and post-lexical phonological processes. Further work will be needed to verify that this proposal can account for the performance of other subjects producing only phonological errors in naming.

Greater number of formal versus nonword errors

As discussed earlier, a mechanism that creates a bias for lexical outcomes generates more word errors than expected by a highly discrete account. However, such a mechanism does not necessarily generate, in absolute numbers, more word than nonword errors. This is because there are many more possible nonword outcomes than word outcomes. Unless lexical bias is extremely strong, we therefore expect to observe more nonwords than words. Consistent with this, several of the studies on lexical bias (discussed earlier) have reported that even though word rates exceeded chance, the number of nonwords produced outnumbered the number of words produced.

However, Nickels (2000) notes that there are aphasic subjects who produce more formal than nonword errors. These subjects produce many error types (semantic, formal word errors, unrelated word errors, and nonword errors) in varying proportions, and show an overall low level of accuracy (less than 50% correct: Best, 1996; Blanken, 1990; Newsome & Martin, 2000)¹⁹. Can this pattern of multiple error types, with a greater number of formal versus nonword errors, be understood under RIA?

First, we note that *unlike* PW and KE, the subjects exhibiting this pattern produced many kinds of errors. As shown in Figure 6, RIA does not produce such a pattern following damage to the semantic or the L-levels; damage to these levels primarily

¹⁹ A potential confound in these studies concerns the neighbourhood characteristics of the target words. If the targets happened to occur in dense phonological neighbourhoods, word outcomes may actually outnumber nonword outcomes (or, more likely, nonword outcomes will simply have a smaller statistical advantage over word outcomes). In this case, phoneme level damage would lead to the pattern of more words than nonwords. Future studies should attempt to control for phonological neighbourhood density.

produces semantic errors. Multiple error types are most readily generated in RIA with damage to the phoneme level.

But what of the advantage for formal error outcomes? Although damage to the phoneme level alone yields multiple error types and a lexical bias effect, formal errors are not produced in greater numbers than nonword errors. There are, however, at least two ways to generate this pattern under RIA. One is to assume that the subjects that exhibit this pattern may have a form of L-level damage different from what we have proposed in other cases. Another is to assume mixed damage affecting both the L and phoneme levels. We discuss each of these possibilities in turn.

Global damage to L-level selection

Thus far we have assumed that damage has an effect comparable to adding noise to processing units. At the L-level the addition of noise decreases the strength of the target, making it more vulnerable to interference from strongly activated competitors. This produces the pattern of only semantic errors in naming. However, subjects who produce more formal than nonword errors may suffer from damage that affects the L-level selection process more *globally*. Specifically, we suggest that with more global L-level damage, the L-level selection process is not only noisier, but also takes longer to settle on a particular L-level unit and, once selection occurs, the selected unit is not set to such a high level.

What consequences might we expect from this form of disruption? In contrast to simply adding noise to L-level units, this more global disruption to the L-level selection process should allow significant numbers of formal errors to arise during L-level selection. We would expect this to occur because the disrupted L-level selection process requires more time, providing cascading activation a chance to build up activity on the phoneme units. This build-up should increase the ability of feedback to boost the activity of formal neighbours at the L-level, increasing their likelihood of being selected during L-level selection.

This form of damage should also result in a full range of error types. As with other cases of L-level disruption, semantic errors should be produced. In addition, an extended L-level selection process should allow feedback to boost the activity of unrelated neighbours as well. Furthermore, as the selected L-level unit is not set to such a high level, Stage 2 processing should not be completely dominated by the selected L-level unit. This should lead to “confusions” at the phoneme level, as the selected L-level unit’s phonemes may not be the most active. This, in turn, should lead to nonword responses.

To test these predictions, we simulated global damage to L-level selection. Recall that the simulation implements L-level selection in a fairly simple manner. L-level selection normally occurs after a pre-determined number of processing cycles. At that point the most active unit is “selected” by having its activation set to a high amount. To disrupt this process, we added noise to the L-level units; increased the number of processing cycles before selection; and then set the selected unit’s activation to a smaller amount than usual²⁰.

²⁰Specifically, L-level noise was set at levels between .2 and .35 (varying levels are shown in Figure 7); instead of the normal 8 processing cycles (or “steps”), 20 steps occurred between conceptual processing and L-level selection; and the selected L-level’s unit activation level (or “jolt”) was set to .02 instead of the normal 4.0 (see Rapp & Goldrick, 2000, for descriptions of the simulation parameters).

These changes succeeded in weakening the L-level selection process and produced the desired pattern of performance (Figure 7). At low levels of accuracy, a variety of error types (semantic, formal, unrelated, and nonword errors) were observed. In addition, the simulation produced formal responses at much greater rates than nonword responses (across the various noise levels, formal errors were observed at least eight times as often as nonword errors). The percentage of responses that are formal or nonword are highlighted by the arrows in the figure.

Mixed L and phoneme level damage

Based on our understanding of processing in RIA, we would also expect that appropriate damage to both the L and phoneme levels would yield the pattern of low accuracy, multiple error types, and more formal errors than nonword errors. Recall that in addition to L-level noise and an increased number of processing cycles, global damage to L-level selection involved setting the selected L-level unit's activity to a lower value than

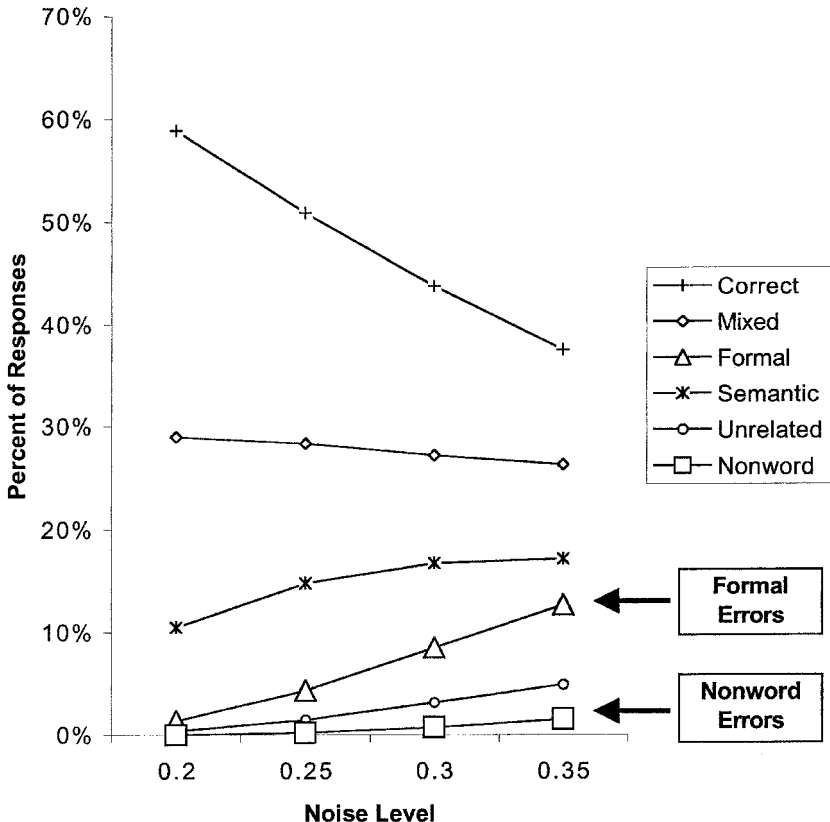


Figure 7. Simulation results (10,000 runs) showing RIA's ability to account for the pattern of more formal than nonword errors. Results are shown at various levels of L-level noise. The arrows highlight the percentage of responses that are formal or nonword errors.

in the intact system. This interferes with the ability of the selected L-level unit to dominate subsequent processing, producing “confusions” at the phoneme level. This constitutes an “indirect” disruption of the phoneme level (see Rapp & Goldrick, 2000, for further discussion of indirect disruption caused by reduced selection strength). Alternatively, instead of disrupting selection strength, one could damage the phoneme level *directly* by introducing noise on the phoneme level units. Under this form of damage, then, the L-level noise and increased processing cycles should produce a variety of word error types (mixed, semantic, formal, and unrelated), while the additional disruption at the phoneme level should produce nonword errors (as well as some additional word errors).

Simulation results confirmed our expectations. Mixed L and phoneme level damage²¹ has the same consequence of global L-level damage: it produces a variety of error types, as well as more formal than nonword errors (under various levels of L-level noise, formal errors occurred at least twice as often as nonword errors).

Which form of damage more accurately reflects the situation in the case reports? Based on the large number of formal errors (in excess of nonword errors), it is clear that these individuals have difficulty in L-level selection. The data do not provide clear evidence as to whether the individuals’ deficits are confined to this process, or whether an additional phoneme level deficit is present. Further research would be needed to distinguish between these two alternatives.

Summary of the challenges for RIA

We have attempted to demonstrate how recent challenges to interactive theories can be accounted for under RIA with extensions to the theoretical framework, rather than through revisions of fundamental assumptions regarding discreteness and interactivity. We have done so by positing that certain deficits take place outside the part of the spoken production system that RIA refers to and that other deficits may involve forms of damage not previously adopted. The fact that certain patterns require explanation outside the representational levels included in RIA is not surprising. The process of spoken production is sufficiently complex that more than three levels of representation are to be expected. With regard to additional forms of damage, it is certainly the case that there are a number of ways in which a system can be damaged and that the addition of noise to a single set of units by no means exhausts these possibilities. It is important to keep in mind that RIA was advanced as a theory regarding discreteness and interactivity in naming and not as a theory of damage. Given this, what is crucial is that there be some reasonable form of damage to the RIA architecture (in keeping with its key theoretical assumptions) that can account for attested patterns of performance.

SUMMARY AND FUTURE DIRECTIONS

Debates concerning the relationship between semantic and phonological processes in spoken production have generally been formulated as a contest between extreme positions where processing is either assumed to be highly discrete or highly interactive. Although there are certainly some advantages to first evaluating the extreme positions, we have argued in this paper that consideration of error data reveals that neither extreme

²¹Specifically, L-level noise was set at levels between .2 and .5; instead of the normal 8 processing cycles (or “steps”), 20 steps occurred between conceptual processing and L-level selection; and phoneme level noise was set to .4 (see Rapp & Goldrick, 2000, for descriptions of the simulation parameters).

is likely to be correct. There is substantial evidence from both normal and aphasic subjects for some degree of interaction within the spoken production system. There is also evidence from aphasic subjects (Rapp & Goldrick, 2000) that is problematic for highly interactive theories and indicates that considerable discreteness is also required.

The restricted interaction account (RIA) responds to the challenges to the highly interactive and discrete proposals by incorporating restricted interactivity. Specifically, under RIA activation is permitted to cascade throughout the system and limited feedback is allowed between the phoneme and L-levels. These features allow the theory to account for interactive effects while, at the same time, generating them only where the data indicate they are needed. Furthermore, RIA, suitably extended, can also accommodate findings that have recently been put forward as being potentially problematic to interactive theories.

In this article we have examined evidence concerning errors produced by normal and impaired subjects. We have left out the substantial literature that specifically examines the time course of semantic and phonological processing. Levelt et al. (1999) present an extensive review of this work and use these findings to construct a detailed and comprehensive theory of production—a theory that, unlike RIA, is highly discrete. As we have shown, such highly discrete theories have significant difficulty accounting for the data from errors—however, Levelt et al. (1999) were primarily concerned with time course data. However, it is also true that RIA's ability to account for time course data has not been systematically explored. Although some findings from time course experiments suggest that semantic and phonological processes interact in production (e.g., Peterson & Savoy, 1998), other findings do not (e.g., Levelt et al., 1991).

Needless to say, much work remains to be done to integrate evidence from reaction time and errors. The hope is that, in combination, such evidence will provide powerful constraints on theory development in the domain of spoken word production.

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