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Analogy and the dual-route model of morphology

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Abstract

Prasada and Pinker's (1993) subjects provided past tense forms of nonce verbs. The subject's willingness to provide irregular past tense forms correlated with the verb's phonological similarity to existing irregular English verbs. However, there was no correlation between the number of nonce verbs assigned regular inflection, and the verb's similarity to existing regular verbs. According to the dual-route model, this is expected since irregular items are stored in associative memory, while regular items take an allomorph of *-ed* by rule. A single-route connectionist simulation failed to duplicate the subject's behavior on regular verbs.

Two instance-based models were applied to the data: Analogical Modeling of Language and the Tilburg Memory Based Learner. Each model employed a similarity algorithm to determine the behavior of all regular and irregular items. Both models successfully mirrored the subject's responses. Therefore, the data are consistent with an instance-based single-route model of morphology. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

One of the central issues that psycholinguists are faced with is determining which morphologically complex words, if any, are stored in the mental lexicon, and which ones are derived productively during speech. Theoretical proposals run the gambit from storing all words (Butterworth, 1983; Bybee, 1985, 1988; Manelis and Tharp, 1977; Stemberger, 1994), to deriving all forms on-line (Taft, 1981, 1985). However, in recent years, the debate has focused on how to account for regular inflectional forms (e.g. *walk* > *walked*), compared to irregular inflectional forms (e.g. *swim* > *swam*).

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Two major positions have emerged. The dual-route model holds that different mechanisms are responsible for regular and irregular inflection (Pinker, 1991; Pinker and Prince, 1988, 1994; Prasada and Pinker, 1993). Accordingly, regular forms are produced on-line by a symbolic rule of morphemic concatenation. Therefore, *walked* is formed by adding one of the regular allomorphs of the past tense morpheme *-ed* (/d, t, ðd/) to the base *walk*. The symbolic rule which adds *-ed* is considered the rule of default. Therefore, it applies to regularly inflected words regardless of their frequency, as well as when the need arises to inflect novel words. Irregular words, in contrast, are stored as wholes in the mental lexicon in an associative network, and their production is a matter of lexical access.

Single-route models assume that regular and irregular morphological patterns may be accounted for with the same mechanism, either massive storage (Bybee, 1985, 1988; Stemberger, 1994) or equal processing of all forms as in connectionism (Daugherty and Seidenberg, 1992, 1994; Elman et al., 1996; Rumelhart and McClelland, 1986; Seidenberg, 1992; see McClelland, 1988 for an introduction to connectionism). Connectionism is perhaps the single-route model that is most widely pitted against dual-route models. It is a computationally-driven model in which all inflected forms, both regular and irregular are derived from their base forms. Morphological and phonological relationships are represented as patterns of activation across sets of units that store mappings between base forms and inflected forms. When a base form is input into the network, the inflection it is given results from the effects of the mappings which the network has encoded.

A great deal of evidence has been amassed in favor of the dual-route model (e.g. Clahsen et al., 1992; Marcus et al., 1995; Pinker, 1991, 1997; Pinker and Prince, 1994; Ullman, 1999), as well as in favor of single-route models (e.g. Bybee, 1995; Marchman, 1997; Nakisa et al., 1998; Seidenberg, 1992; Seidenberg and Bruck, 1990; Sereno and Jongman, 1997; Stemberger and MacWhinney, 1986, 1988). It is difficult to come to any definite conclusions on the issue since the relevant literature is replete with findings and counter-findings, explanations and alternative explanations. For example, Jaeger et al. (1996) found neurological evidence that regular and irregular inflections are processed by different areas of the brain, which appears to support the dual-route model (see also Marslen-Wilson and Tyler, 1997; Penke et al., 1997). However, others (Chandler and Skousen, 1997; Seidenberg and Hoeffner, 1998) argue that these findings can be explained within a single-route model. Arguing in behalf of the dual-route model, Prasada et al. (1990) found frequency effects for irregular English past tense forms, but no frequency effects for regular forms.¹ However, in a connectionist network, Daugherty and Seidenberg (1992, 1994) also obtained frequency effects for irregular items, and none for regular items.

In like manner, evidence that originally went in favor of the connectionist version of the single-route model has been found lacking. For example, many flaws in

¹ There is a possible confound in this study. The average frequency difference between the high and low frequency irregular test items in each pair was 60.8 words per million. The average gap between the pairs of regular items, however, was only 20.8, hence the dissociation between regular and irregular items in the study.

Rumelhart and McClelland's (1986) simulation of the English past tense were brought to light (Lachter and Bever, 1988; Marcus et al., 1992; Pinker and Prince, 1988). This led to further connectionist simulations which were designed to address some of the specific weaknesses of Rumelhart and McClelland's study (Daugherty and Hare, 1993; Cottrell and Plunkett, 1994; MacWhinney and Leinbach, 1991; Plunkett and Marchman, 1993). However, problems with these revised simulations have also been found (Marcus et al., 1995; Marcus, 1995, 1998).

I would like to suggest that the debate between dual- and single-route models has been narrowed into a debate between the dual-route model, as espoused by Pinker and his associates, and particular connectionist versions of the single-route model. In fact, the theoretical adequacy of the single-route model is often judged solely in terms of the adequacy of a particular connectionist model. Of course, this may be due to the fact that connectionism lends itself more easily to empirical test when compared with other proposed single-route models (e.g. Bybee, 1985, 1988; Stemberger, 1994). If connectionism were found to be a completely invalid way of modeling human language, it would not necessarily imply that all single-route models follow suit. The adequacy of other single-route models needs to be explored before fair judgement may be passed on the idea that regular and irregular inflection may be accounted for by means of a single mechanism.

The purpose of the present paper, then, is to discuss two exemplar-based single-route models, namely Analogical Modeling of Language (AML) (Skousen, 1989, 1992, 1995) and the Tilburg Memory Based Learner (TiMBL) (Aha et al., 1991; Daelemans et al., 1999). After a brief overview of these approaches, I will demonstrate that they are able to mirror the results of an experiment that has been presented as evidence against the single-route model. The fact that a connectionist simulation of the same experiment was unable to produce similar results argues in favor of exemplar-based instantiations of the single-route approach.

2. Analogical Modeling of Language

AML is a model of how memory tokens may be used to predict linguistic behavior. In this regard, it is similar to other instance-based models (Bod, 1998; Medin and Schaffer, 1978; Nosofsky, 1988, 1990; Riesbeck and Schank, 1989; see Shanks, 1995, for an overview of exemplar-based models). In AML, all regular and irregular forms are attributed to the same mechanism. For this reason it is reminiscent of connectionism. Neither model extracts overall characterizations of the data in the form of a rules or schemata.

There are, however, significant differences between AML and connectionist models (Chandler, 1995; Jones, 1996; Skousen, 1989, 1995). Connectionist networks predict only one outcome for a given context, while AML predicts the probability that one or more outcomes will be chosen. Connectionist networks require extensive training and feedback from a 'teacher' while AML does not entail any sort of training or external teacher. In connectionism, information is stored as patterns of activation in a network of interconnected nodes; there is no representation of individual

words. In AML, the information is contained in a database of exemplars representing the contents of the mental lexicon. This database may be added to at any time. In contrast, connectionist networks cannot readily accept new data without having to be completely retrained to include the new data.

In AML, when the need arises to determine some linguistic behavior, (choice of allomorph, speech variant determined by sociolinguistic context, affix, etc.), a search of the database is conducted beginning with the entries most similar to the given context in question, and then extending to less similar entries. The algorithm contains an explicit procedure for assembling an analogical set from which analogs may be chosen, and subsequently applied to the given context. AML calculates the probability that one or more behaviors will apply to the given context. In general, database entries most similar to the given context will appear in the analogical set. However, unlike other analogical models, less similar items have a smaller chance of being included as well. In addition, AML makes no advance determination of which variables are most relevant for the task.

Perhaps the best way to understand the AML algorithm is with a concrete illustration. Predictions are always made in terms of specific exemplars, therefore, for the purposes of the example, the following seven monosyllabic verbs, and whether their corresponding past tense form is regular or irregular, will be considered: *sing irr.*, *thin reg.*, *gun reg.*, *stink irr.*, *drown reg.*, *sip reg.*, and *load reg.* The task will be to predict whether the verb *sin* has a regular past tense form or not on the basis of these seven items as the database. For the purposes of this example, three variables will be considered: the phoneme or phoneme cluster of the onset, nucleus, and coda. For the sake of clarity, graphemic instead of phonemic transcriptions are used in the tables. To begin, all possible database items are assigned to a series of subcontexts which are defined in terms of the given context *sin*. For the task at hand, there are eight subcontexts (Table 1). A bar over a variable indicates that any value of the variable except the barred value is permitted in the subcontext. Disagreements are marked with asterisks.

By assigning members to subcontexts it is possible to determine disagreements. A disagreement occurs when two words, that are equally similar to the given context, exhibit different behavior, in this case, differences in regularity. The number of disagreements is determined by pairing all members of a subcontext with every other member, including itself, by means of unidirectional pointers, and counting the number of times the members of the pair have different behaviors. In this example, the only subcontext containing any disagreement is $s\bar{i}\bar{n}$.

Once the disagreements have been found, the subcontexts are arranged into more comprehensive groups of subcontexts called supracontexts. In Table 2, a hyphen indicates a wildcard.

The subcontextual analysis consists of adding all of the subcontextual disagreements which appear in each supracontext. The next step is to perform a supracontextual analysis which consists of analyzing all of the words that appear in a given supracontext, and determining disagreements (Table 3).

In the supracontextual analysis, it can be seen that words that have more than one feature in common with *sin* appear in more than one supracontext. This is AML's

Table 1
Subcontexts and their disagreements

Subcontexts	Members of the subcontext	Pointers	Number of disagreements
s i n	none	none	0
š i n	<i>thin reg.</i>	<i>thin reg.</i> → <i>thin reg.</i>	0
s ī n	none	none	0
s i ñ	<i>sing irr., sip reg.</i>	<i>sing irr.</i> → <i>sing irr.</i> <i>sip reg.</i> → <i>sip reg.</i> <i>*sing irr.</i> → <i>sip reg.</i> <i>*sip reg.</i> → <i>sing irr.</i>	1 2
š i ñ	<i>stink irr.</i>	<i>stink irr.</i> → <i>stink irr.</i>	0
š ī n	<i>gun reg., drown reg.</i>	<i>gun reg.</i> → <i>gun reg.</i> <i>drown reg.</i> → <i>drown reg.</i> <i>gun reg.</i> → <i>drown reg.</i> <i>drown reg.</i> → <i>gun reg.</i>	0
s ī ñ	none	none	0
š ī ñ	<i>load reg.</i>	<i>load reg.</i> → <i>load reg.</i>	0

Table 2
Subcontextual analysis

Supracontext	Subcontexts in supracontext	Number of subcontextual disagreements
s i n	sin	0
s i -	sin, *siñ	2
s - n	sin, sīn	0
- i n	sin, šin	0
s - -	sin, sīn, *siñ, sīñ	2
- i -	sin, šin, *siñ, šin	2
- - n	sin, sīn, sīn, šin	0
= = =	sin, šin, sīn, *siñ, šin, sīn, sīñ, sīñ	2

way of allowing the behavior of verbs which are more similar to *sin* to influence *sin* to a greater extent.

The purpose of AML's algorithm is to determine which members of the database are most likely to affect the inflection of *sin*, and also to calculate the extent of analogical influence exerted. Much of this is accomplished by calculating heterogeneity. Heterogeneity is determined by comparing the number of disagreements in the supracontextual and subcontextual analyses. If there are more disagreements in the supracontextual analysis, the supracontext is heterogenous, and its members are eliminated from consideration as possible analogs. If the number of disagreements does not increase, the supracontext is homogenous. Words belonging to homogenous supracontexts comprise the analogical set. In the example under consideration, disagreements increase in the supracontexts = = =, and - i -. Therefore, their members are

Table 3
Supracontextual analysis

Supracontext	Words in supracontext	Pointers	Number of subcontextual disagreements
s i n	none	none	0
s i -	<i>sip reg.</i> , <i>sing irr.</i>	<i>sing irr.</i> → <i>sing irr.</i> <i>sip reg.</i> → <i>sip reg.</i> * <i>sing irr.</i> → <i>sip reg.</i> * <i>sip reg.</i> → <i>sing irr.</i>	2
s - n	none	none	0
- i n	<i>thin reg.</i>	<i>thin reg.</i> → <i>thin reg.</i>	0
s - -	<i>sip reg.</i> , <i>sing irr.</i>	<i>sing irr.</i> → <i>sing irr.</i> <i>sip reg.</i> → <i>sip reg.</i> * <i>sing irr.</i> → <i>sip reg.</i> * <i>sip reg.</i> → <i>sing irr.</i>	2
- i -	<i>thin reg.</i> , <i>stink irr.</i> , <i>sip reg.</i> , <i>sing irr.</i>	<i>thin reg.</i> → <i>thin reg.</i> * <i>thin reg.</i> → <i>stink irr.</i> <i>thin reg.</i> → <i>sip reg.</i> * <i>thin reg.</i> → <i>sing irr.</i> <i>stink irr.</i> → <i>stink irr.</i> * <i>stink irr.</i> → <i>thin reg.</i> * <i>stink irr.</i> → <i>sip reg.</i> <i>stink irr.</i> → <i>sing irr.</i> * <i>sing irr.</i> → <i>thin reg.</i> * <i>sing irr.</i> → <i>sip reg.</i> (not all shown; all the rest involve agreement)	6
- - n	<i>thin reg.</i> , <i>gun reg.</i> , <i>drown reg.</i>	(not shown)	0
= = =	<i>thin reg.</i> , <i>gun reg.</i> , <i>drown reg.</i> , <i>stink irr.</i> , <i>sing irr.</i> , <i>sip reg.</i> , <i>load reg.</i>	(not shown)	12

eliminated from consideration. *Stink* and *load* appear exclusively in these heterogeneous supracontexts. As a result, they do not form part of the analogical set. *Thin* is also a member of both = = = and - i -, however, it is also a member of the homogeneous supracontexts - i n, and - = n, so it will still be available to influence *sin*.

It should not be surprising that *load* would be eliminated through heterogeneity; it has no phonemes in common with *sin*. However, consider the words *drown* and *stink*. Both share only one variable with *sin*, yet heterogeneity eliminates only *stink*, and not *drown*. This is due to the fact that *drown* appears in the supracontext - = n, and all of the members of that supracontext have regular past tense forms, therefore, there is no disagreement. *Stink*, on the other hand, competes with words with regular past tense forms in all of the supracontexts in which it appears.

As already mentioned, the analogical set (Table 4) includes words from all non-empty homogenous supracontexts.

Table 4
Non-empty homogenous supracontexts

Homogenous supracontext	Words in supracontext	Pointers	# of pointers to regular	# of pointers to irregular
s i -	<i>sip reg.</i> , <i>sing irr.</i>	<i>sip reg.</i> → <i>sip reg.</i> <i>sip reg.</i> → <i>sing irr.</i> <i>sing irr.</i> → <i>sip reg.</i> <i>sing irr.</i> → <i>sing irr.</i>	2	2
- i n	<i>thin reg.</i>	<i>thin reg.</i> → <i>thin reg.</i>	1	0
s - -	<i>sip reg.</i> , <i>sing irr.</i>	<i>sip reg.</i> → <i>sip reg.</i> <i>sip reg.</i> → <i>sing irr.</i> <i>sing irr.</i> → <i>sip reg.</i> <i>sing irr.</i> → <i>sing irr.</i>	2	2
- - n	<i>thin reg.</i> , <i>gun reg.</i> , <i>drown reg.</i>	(not shown)	9	0

The analogical set contains all of the database items that can possibly influence the regularity of *sin*. There are two methods for calculating the influence of the analogical set on the behavior of the given context. One is to assign the most frequently occurring behavior to the given context (selection by plurality). Of the 18 pointers in the set, 14 point to regular items. Therefore, selection by plurality would assign regular past tense inflection to *sin*. The other method (random selection) involves randomly selecting a pointer, and assigning the behavior of the word indicated by the pointer to the given context. In this case, the probability of regularity would be 77.78% (14/18). Random selection allows the fuzziness between behaviors to be calculated, something which is not possible in either a rule-model or a connectionist simulation.

3. Tilburg Memory Based Learner

The nearest neighbor model used in the present study is that of Daelemans et al. (1999), which itself is an expansion of the model developed by Aha et al. (1991; see Daelemans et al., 1994, for a comparison of AML and the nearest neighbor model of Aha et al. 1991). During the training session, the model is fed series of variables which represent instances of words (or some other entity). These are stored in memory along with the behavior the word displays (e.g. the allomorph or affix taken by the word). In the case that the same word is encountered more than once, a count is kept of how often each word is associated with a given behavior. The model is also able to calculate how much each variable contributes to determining the correct

behavior, and weights these variables accordingly. During the testing phase, when a word is input, the model searches for it in memory and applies the behavior that it has been assigned in the majority of cases. If the word is not found in memory, a similarity algorithm is used to find the most similar item in memory – its nearest neighbor.² The behavior of the nearest neighbor is then applied to the word in question. If two or more items are equidistant from the word in question, the most frequent behavior of the tied items is applied to the word in question.

4. Prasada and Pinker (1993)

The principal purpose of the present study is to compare AML and TiBML to Prasada and Pinker's study of the English past tense (1993, henceforth P&P). In the past decade, the English past tense has become a testing ground for the adequacy of single- and dual-route models, which is why alternative single-route accounts of the data are warranted. P&P propose a dual-route model in which irregular past tense forms have individual lexical entries, and are stored in an associative network. This allows words that are similar to existing irregulars to be influenced to take an irregular past tense as Bybee and Slobin (1982), and Bybee and Moder (1983) have demonstrated.

In the strongest form of their model, regularly inflected past tense forms are completely predictable, and as a result, are not stored. Instead, they receive their inflection by means of a rule which essentially adds *-ed* to the stem. Given this state of affairs, the phonological shape of a regularly inflected past tense form should never be a factor that affects the inflection of novel verbs. Pinker has retreated somewhat from this strong stance, and admits the possibility that some high frequency regular inflections may have individual representation in memory (Pinker and Prince, 1994: 331). However, even if some regular items are stored, P&P maintain that "generalization never depends on prior storage of a similar form, so it should never fail outright, even for very unusual sounding forms" (1993: 9). Single-route models differ significantly from this position in that phonological similarity to extant words is necessary in order to generate both regular and irregular past tense forms.

If irregular inflection depends on phonological similarity, but regular inflection does not, there should be a testable difference between people's perceptions and behavior in regards to regular and irregular items. P&P suggest that "the crucial question is whether strong dissimilarity to regulars (as opposed to strong similarity to irregulars) is a condition causing people to be queasy about applying the regular inflection to a novel verb" (1993: 7–8). In order to test this, they constructed a series of nonce verbs. Each set contained 10 items. The *prototypical pseudo-irregular* class contained nonce items that rhyme with several irregular verbs. For example, *froe*

² This model includes several different algorithms for determining similarity, and also allows several nearest neighbors to be chosen as analogs (see Daelemans et al., 1999). For the purposes of the present study, the overlap method with information gain weighting was applied. Only one nearest neighbor was calculated.

rhymes with *blow*, *throw*, *know* which have past forms in [uw]; *spling* rhymes with *spring*, *ring*, *fling*. *Intermediate pseudo-irregular* items were devised to be less similar to existing irregular forms. They were formed by changing the initial or final consonant cluster of a *prototypical pseudo-irregular* item (e.g. *froe* > *voe*, *spling* > *ning*). *Distant pseudo-irregular* items were designed to be even more phonologically distant from verbs with irregular past tense forms. They differ in both their initial and final consonant clusters from *prototypical pseudo-irregular* items (e.g. *spling* > *nist*, *froe* > *goav*).

Three groups of pseudo-regular nonce items were also created that progressively differ in the extent to which they resemble existing regular past tense forms. Nevertheless, they all contain the same vowels as the irregular nonce items (i.e. /ɪ, ow, i, ej/). Since these vowels occur in verbs which take an irregular past tense form, this made the option of choosing an irregular past tense more plausible. *Prototypical pseudo-regular* items, such as *treem*, were chosen which rhyme with other regular verbs (e.g. *cream*, *seem*, *steam*). Where possible, *intermediate pseudo-regular* words have initial consonant cluster plus vowel sequences that are unattested in English verbs, and end with vowel plus consonant clusters that are unattested as well. However, the word-final consonant clusters of these words do exist in other verbs. The *distant pseudo-regular* nonce items differ from the latter class in that their word-final consonant clusters do not appear in English verbs.

P&P performed a number of experiments with these items. They had subjects rate the nonce verbs in terms of their 'naturalness', and in terms of the likelihood that a given verb would take a certain past tense form. In another study, the subject's task was to actually inflect the test items. The results of all of these experiments were in the same direction. However, the outcome of the inflection experiment is most germane to the present study, since it lends itself to direct comparison with AML and TiBML.

P&P found the following in their inflection experiment. As the irregular nonce verbs moved from being similar to real irregular verbs (*prototypical pseudo-irregular*), to somewhat dissimilar (*intermediate pseudo-irregular*), to highly dissimilar to existing irregular past tense verbs (*distant pseudo-irregular*), the subjects became less likely to give them an irregular inflection. This is consistent with the idea that the irregulars are stored in memory and are thus available to exert analogical influence on the nonce verbs.

Quite a different pattern emerged as the pseudo-regular nonce verbs moved from having a great deal in common with existing regular verbs, to having a phonological shape unlike any English verb. In this case, there was no significant difference between the number of regular past tense forms given to nonce verbs in each of the three conditions of similarity (prototypical, intermediate, and distant). In other words, phonological similarity seems to have played no role in the subjects' choice of regular or irregular conjugation. P&P claim that this finding is expected if regular inflection consists of adding *-ed* by rule, but would be unexpected if regular inflection required the nonce items to be phonologically similar to other regular past tense forms stored in memory. The subjects had no difficulty producing regular inflection in spite of the fact that the nonce verbs were highly dissimilar to any known verbs.

A single-route model would presumably have predicted change as the nonce verbs moved away from attested phonological patterns.

5. P&P's connectionist simulation

In order to drive their point home more forcefully, P&P performed a connectionist simulation. The network was trained on the same verbs used in the study by Rumelhart and McClelland (1986). Once the network was trained, it was used to predict the past tense form of the 60 nonce verbs that were inflected by the subjects in the previous study. The network produced some highly unusual past tense forms that bore little resemblance to the stem. For this reason, P&P considered only the irregular past tense forms that involved a vowel change. Suffixed responses are those that take one of the allomorphs of the regular *-ed* suffix. The network's output, and the responses of the subjects appear in Figs. 1 and 2 (taken from P&P, Fig. 5).

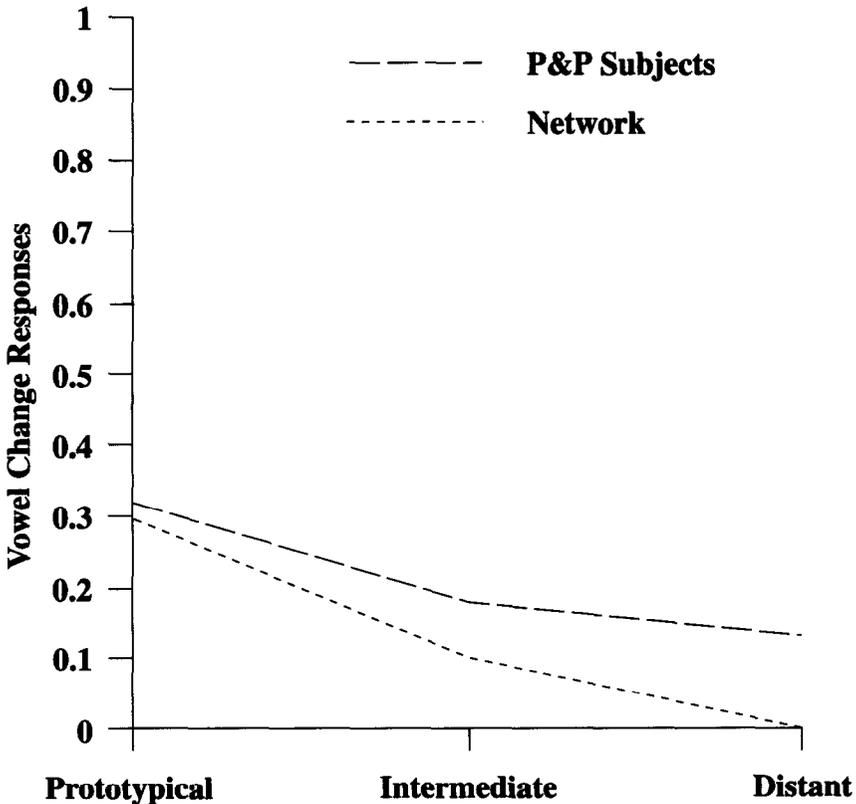


Fig. 1. Mean number of vowel change past tense forms provided by the subjects and the connectionist network.

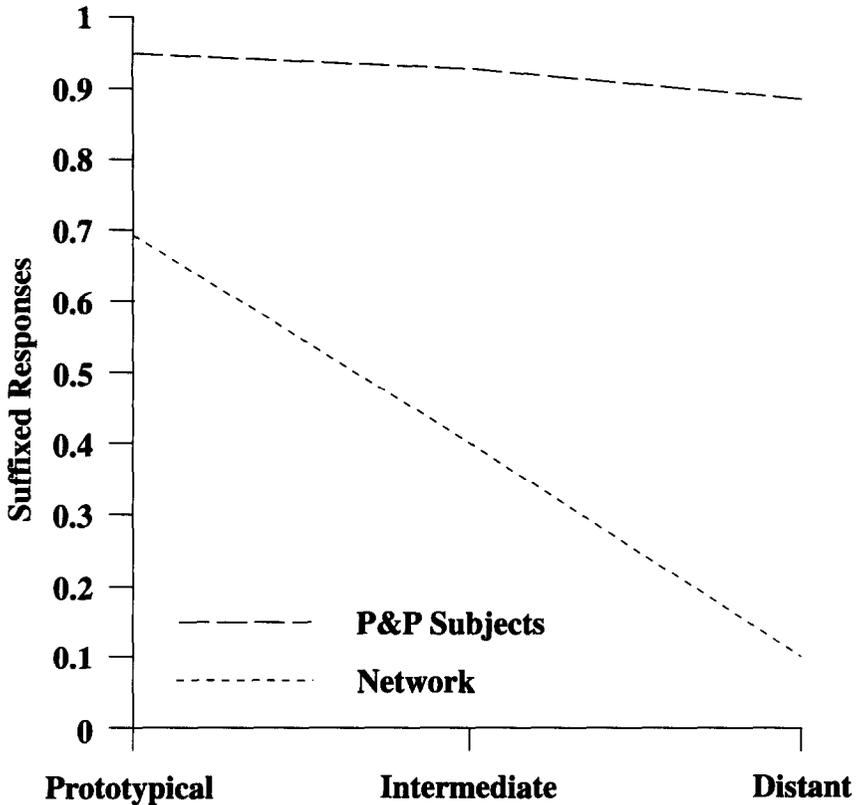


Fig. 2. Mean number of regularly suffixed past tense forms provided by the subjects and the connectionist network.

It is clear that the network was able to handle the irregular nonce items in the same way as the subjects. However, the subjects provided regular inflections on most of the pseudo-regular nonce items in spite of the fact that many of these had an extremely unusual phonological shape. The network, on the other hand, provided fewer regularly suffixed responses as the nonce items became less similar to existing verbs. P&P consider this *prima facie* evidence that regular inflection does not depend on similarity to existing verbs, while irregular inflection does. The fact that this single-route connectionist simulation is unable to mirror the subject's responses is regarded as evidence against the single-route model, and in favor of the need for separate mechanisms to handle regular versus irregular inflection.

6. Alternative single-route simulations of the nonce words

As stated earlier, it is premature to discount the idea of a single-route mechanism of inflection on the basis of the inadequacies of one of its possible instantiations. For

this reason, the TiBML and AML models were put to the test. Exemplar-based models always make their predictions on the basis of a database of tokens. Therefore, it was important to design a database that is representative of what might exist in the mental lexicon of an English speaker. Psycholinguistic experimentation has shown that high frequency words are accessed more rapidly than low frequency words (e.g. Allen et al., 1992; Scarborough et al., 1977). In addition, high frequency items are less subject to error than low frequency items (e.g. MacKay, 1982). This suggests that frequent forms are more readily available, and therefore, more likely to be selected as analogs. Therefore, the 848 most frequent English verbs were extracted from the Brown corpus (Francis and Kučera, 1982) and constituted the analogical database.

Each of these verbs was encoded into 10 variables which include the phonemic content of the penult rhyme and final syllable of the verb's present tense stem. It also includes the stressed or stressless status of the verb's final syllable. This encoding was found to be optimal in Derwing and Skousen's (1994) acquisitional study of the English past tense. Phonemes were assigned starting with the syllable nuclei and working outward. The first missing phoneme was marked with '0', and any additional empty slots were marked with the null symbol '=' (see Table 5).

Table 5
Assignment of variables

Penult syllable:

1. The penult vowel, or '0' if there is none.
2. The first phoneme following the penult vowel.
3. The second phoneme following the penult vowel.

Final syllable:

4. The second phoneme preceding the final vowel.
5. The first phoneme preceding the final vowel.
6. The final vowel.
7. The first phoneme following the final vowel.
8. The second phoneme following the final vowel.

Stress:

9. '1' if the final syllable is stressed, '0' if it is stressless.

Final phoneme:

10. The verb's final phoneme.

In addition to these variables, each verb stem was marked to indicate its inclusion in one of three categories. These categories were chosen to facilitate comparison with P&P's study:

- A. Regular past tenses formed by the addition of [t], [d], or [+d] to the stem.
 - B. Irregular past tenses formed with a vowel change, or a vowel change plus another change to the stem (e.g. *get* > *got*; *seek* > *sought*).
 - C. Other irregular past tenses formed without a change in vowel (e.g. *make* > *made*, *hit* > *hit*).
-

Once the training set of 848 items was constructed, the 60 nonce items from P&P's experiment were also encoded in like manner. These comprised the test set. The algorithms for TiBML and AML were applied to each of the test items.

6.1. P&P's nonce verbs in AML

AML compared the test items to the items in the training set, produced an analogical set for each item, and calculated the probability that each nonce word would have a regular past tense form, an irregular past tense with a vowel change, or an irregular past tense form without a vowel change. For example, *froe* was given a 0.52 probability of having a regular past tense form, and 0.48 probability of having a past tense form with a vowel change. In like manner, *queef* was given an 0.87 probability of having a regular past tense form, and a 0.13 probability of having a past tense form with a vowel change.

For the pseudo-irregular nonce items, the average predicted probability that the words in each category (prototypical, intermediate, and distant) would take an irregular past tense was 0.32, 0.33, and 0.21 respectively. The average probability that the pseudo-regular nonce items would have a regularly inflected past tense form was 0.96, 0.87, and 0.92 in each category.

6.2. P&P's nonce verbs in TiBML

The TiBML approach calculated the most similar verb in memory to each of the nonce verbs, and then applied the behavior of the nearest neighbor to the nonce verb. For example, the nearest neighbor of *queef* is 'quote', which makes the past tense regular *queefed*. The nonce verb *froe* yielded two equidistant nearest neighbors, 'grow', and 'throw'. Since they both appear only once in the database, and have the same type of irregular past tense form, the past tense of *froe* is predicted to be irregular with a vowel change (*frew*). For the pseudo-irregular nonce items, the average number of nonce verbs in each category (prototypical, intermediate, and distant) that were predicted to take an irregular past tense was 0.4, 0.4, and 0.2 respectively. The average number of pseudo-regular nonce items that were assigned a regularly inflected past tense form was 1.0, 0.9, and 1.0 in each category.

6.3. Comparison of the experiments

P&P excluded from consideration any irregular past tense forms which did not involve a vowel change. This was done due to some erratic outputs given by the connectionist network in which the past tense form no longer appeared to be related to its stem. Therefore, in order to compare the alternative single-route model results with those of P&P, all probability that an irregular past tense without a vowel change would occur was eliminated from the AML predictions. In no cases did the TiBML predictions involve past tense forms without vowel changes. Fig. 3 and 4 show how AML and TiBML compare to the previous study by P&P.

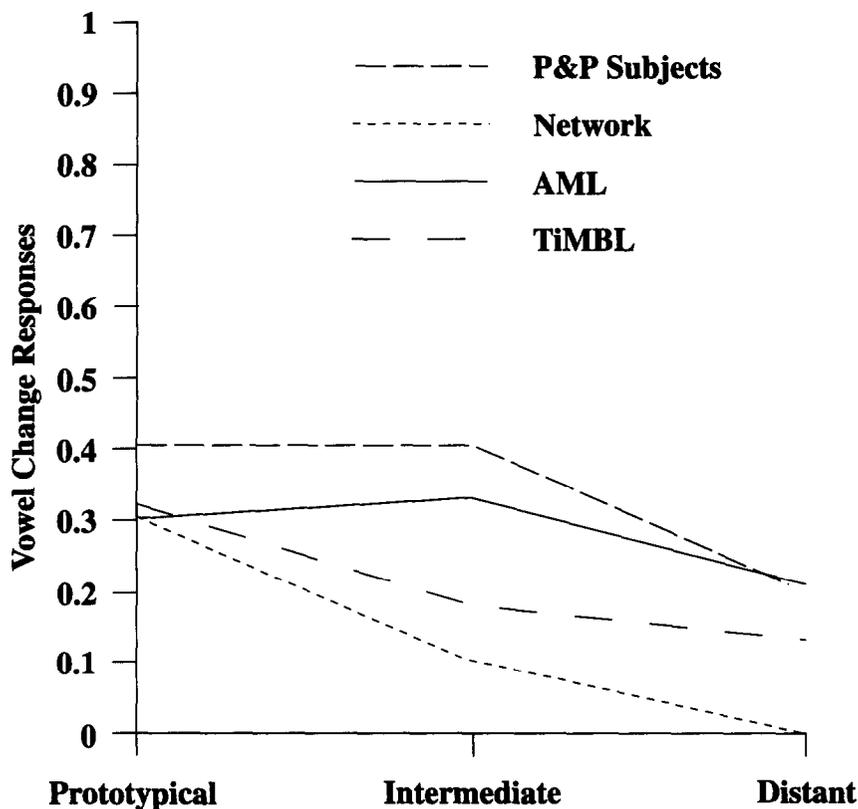


Fig. 3. Mean number/probability of vowel change past tense forms.

The predictions made by the TiMBL and AML models mirror the subjects' choices quite closely. The probability that a pseudo-irregular item would take an irregular past tense form decreased as the nonce items became less similar to extant irregular forms. TiMBL and AML showed no decrease between the prototypical and intermediate groups, but did register a fall for the distant group. However, the connectionist model was also able to model this trend. The most important finding regards the predictions for the pseudo-regular items. Subjects provided few irregular inflections in any of the three pseudo-regular groups, in spite of the fact that the intermediate and distant nonce verbs had odd phonological shapes. The connectionist model produced mainly regular inflections for the *prototypical pseudo-regular* items, but produced consistently less regular inflections as the nonce items became phonologically distant from attested verbs.

AML's and TiMBL's predictions for the pseudo-regular items, on the other hand, follow those of the subjects. As in connectionism, the phonological shape of existing verbs provided the basis for determining the past tense form of the nonce verbs in the analogical simulations. Nevertheless, the outcomes differ drastically. The AML

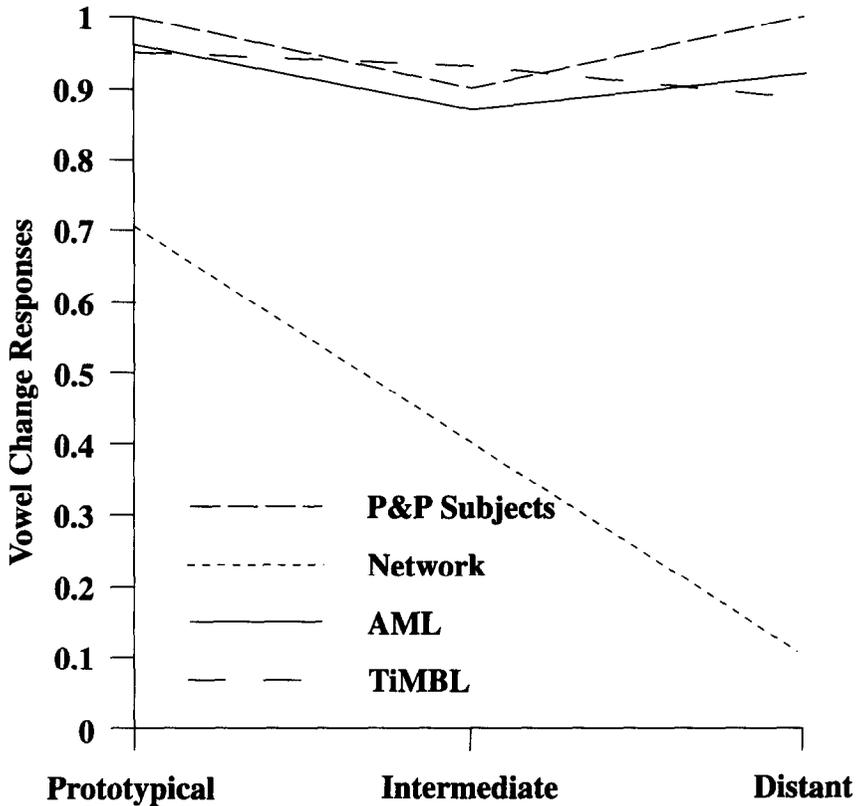


Fig. 4. Mean number/probability of regularly suffixed past tense forms.

and TiMBL approaches had no difficulty assigning regular inflection to the phonologically odd nonce items in the same way the subjects did.

7. Conclusions

The failure of the connectionist simulation to model the subjects' choices was taken by P&P as evidence that the single-route model was severely flawed. However, in light of outcome of the present study, if there is a flaw, it may exist in the particular connectionist simulation used, not in the single-route model per se. Moreover, AML and TiMBL successfully predicted the subjects' choices of past tense form for both regular and irregular items, and it did so by comparing the nonce words to words in the database in terms of their phonological similarity. In short, the present study demonstrates that the evidence adduced by P&P in favor of the dual-route model is actually consistent with a single-route model. It is hoped that the debate between single- and dual-route models will be broadened to include other

models, such as TiBML and AML, which may prove to have advantages over their connectionist counterparts.

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