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Constraining psycholinguistic models of morphological processing and representation: the role of productivity*

ULI H. FRAUENFELDER AND ROBERT SCHREUDER

1. INTRODUCTION

Listeners can understand novel lexical forms without apparent difficulty. This ability to analyze and interpret an unfamiliar input string raises some important psycholinguistic questions. We are led to ask how this parsing is actually accomplished and what its role is in the recognition of familiar word forms. The standard psycholinguistic answer to the latter question has been that the human parsing abilities at the lexical level are of only minor importance. Indeed, in modeling lexical processing, psycholinguists have not been particularly concerned with morphological productivity and its implications for lexical processing and storage. This neglect of productivity is clearly apparent in the default view of language comprehension which is assumed to be based upon two radically different processing mechanisms. The first is exploited during word recognition and involves retrieving information from a permanent memory store, the lexicon. The second mechanism allows the integration of the semantic and syntactic information associated with the individually recognized words and their order. These latter processes parse and construct novel sentential representations. Thus, the mechanisms that are capable of generating new linguistic structure are typically reserved for the post-lexical processes.

Baayen (this volume) does us a big service by helping to reinstate the issue of morphological productivity on the psycholinguistic agenda. In order to make the notion of productivity more useful for (psycho)linguistic theorizing, he develops a quantitative definition of productivity based upon word token frequencies. In this paper, we will be concerned primarily with the issue of morphological productivity and its implications for models of morphological processing in word recognition. We first consider two widely accepted constraints or principles that are concerned with the economy of storage and the economy of processing, respectively. After examining how these two opposing principles have constrained models of word recognition, we turn our attention to a third constraint, that of morphological productivity. We examine models that are intended to deal with productivity, including that proposed by Baayen. In the concluding section, some limitations of Baayen's proposal are discussed and an alternative model is presented.

2. CONSTRAINTS ON MORPHOLOGICAL PROCESSING AND REPRESENTATIONS

A wide range of word recognition models has been proposed to describe the

processing and representation of morphological information. These can be organized along a continuum with, at one extreme, models with full listing and direct access (Butterworth 1983; Manelis and Tharp 1977), and at the other, the models assuming decomposed lexical representation and morphological parsing (Taft 1985, Taft and Forster 1975). The former models assume that each morphologically complex word is stored as a single unit, and that word recognition involves the direct retrieval of this whole word unit. According to the models with morphological decomposition, all morphologically complex words are obligatorily decomposed into their bases and affixes. These two model types are motivated by two opposing principles: the first by the principle of economy of processing and the second by the principle of economy of storage. We will consider these two constraining principles, before addressing the issue of productivity.

2.1. Economy of storage constraint

The economy of storage argument from a psycholinguistic point of view runs as follows. The listing in the lexicon of word forms requires storage space and thus introduces a memory load. The total amount of storage varies roughly with the number of items being stored. Furthermore, the efficiency with which a particular lexical item can be retrieved — for example, its look-up time — depends upon the number of stored forms that need to be searched. If one assumes fixed limits to the brain's capacity for storing lexical knowledge or limits to the allowable search times, then the number of lexical entries becomes a critical factor. This principle of economy of storage suggests that it is desirable to restrict the number of stored lexical entries and to avoid a full-listing approach. It should be noted that it is too simplistic to claim that only the number of stored forms counts in defining storage costs. Clearly the way in which the forms are stored must be taken into consideration. Presumably the storage costs can be reduced considerably by organizing word forms according to their morphological families (Segui and Zubizarreta 1985) or into some network structure.

By storing morphemes rather than individual words, the lexicon can make savings in the storage of two different types of representations: the access representations of form, and the semantic representations. In the case of semantic representations, storage can be saved for those word forms where the combination of stem and affix is compositional, i.e. can be computed from the meaning of the stem and the meaning of the affix.

Hankamer (1989) appeals to the economy of storage principle to argue against the full listing hypothesis when applied to agglutinative languages like Turkish. On the basis of a study of the forms generated by his morphological parser for Turkish (Hankamer 1986), he claims that about 2 million forms were produced for verb forms (without any recursion). With one level of recursion, this number jumps to about 27 million. The figures for nouns are even more impressive with 9 million and 217 million without and with recursion, respectively. When estimating the lexicon size of a typical educated speaker of Turkish at 20 000 noun roots and 10 000 verb roots, he com-

puted that a full-listing lexicon would contain over 200 billions entries. Hankamer argues that the storage capacity of the brain (1.25×10^{13} bytes) would be insufficient to store all these words, and concludes that the full listing hypothesis cannot be maintained for agglutinative languages.

Although plausibility arguments like these are seducing, we should stress that the importance of the economy of storage principle in constraining word recognition models remains an empirical issue. This situation is quite different in linguistics where limiting the number of representations stored in the lexicon is motivated by concerns with the elegance and parsimony of the formal theory.

2.2. Economy of processing constraint

According to this principle, it is easier to retrieve a full form directly than to parse it. Parsing requires mental computations, and these computations, in their turn, involve processing costs. This principle claims that processing costs should be minimized, and therefore, direct look-up is preferable to decomposition or parsing. The arguments against parsing are further strengthened by the observation that parsing cannot always proceed smoothly, given the structure of words. The difficulties encountered in parsing are assumed to lead to even greater processing costs.

A first major difficulty is that there often exist several alternative parses for a given input. The parser has to determine which analysis is correct — perhaps by appealing to other sources of information. A second major problem is that parsing will not always be successful as in the case of pseudo-affixes or pseudo-stems. Indeed, many affixes and stems have homographic or homophonic sequences that make the parser's chore more difficult. In dealing with such pseudo-affixed forms (e.g., *repertoire*), the parser parses the pseudo-prefix (*re*) and then attempts to identify the remaining string (*pertoire*) as another morpheme (i.e. stem). The parser then discovers that the second string is not stored in the lexicon as a morpheme and must use a direct route. This initial unsuccessful parse and the subsequent reanalysis are assumed to be costly. For many languages the success rate of the first-pass parse is surprisingly low. In an analysis of the large English and Dutch database (CELEX), Schreuder and Baayen (in preparation) have shown that parsing is not efficient for prefixes. Typically, the success rate, weighted for token frequency, ranges between 30 and 50 percent.

Even if a parse is successful, and the input string can be identified correctly as being a stem and its affix, problems arise in the case of bound stems, or opaque word forms whose meaning cannot be derived by combining that of the stem and affix. In these cases the meaning of the combination has to be stored separately, and, therefore, no economy of memory storage of semantic representations is achieved.

2.3. Economy of processing versus economy of storage

The basic question of whether the economy of storage or the economy of

processing (or neither) is most important in constraining models of word recognition remains largely unanswered. This is essentially an empirical question that must be addressed by experimental research. Unfortunately, the experimental literature has given no clear cut answers so far (see Henderson 1985, 1986, for a review of the relevant studies). With respect to the issue of processing cost, Cutler (1983) concludes that there is no unequivocal empirical evidence in the experimental literature demonstrating that morphologically complex words are more difficult to process (i.e. take more time to process) than mono-morphemic words. Such null evidence does not prove, of course, that morphologically complex forms are not parsed during word recognition. It just shows that *if* such parsing is done, it is either being done very efficiently and/or the experimental techniques are not up to measuring these effects.

Similarly no demonstration exists to date that economy of storage must be taken seriously in modeling. The argument that there are serious storage limitations was questioned by Landauer's (1986) theoretical work on the amount of information that can be stored in the human brain. Landauer (1986: 493) concludes that "... possibly we should not be looking for models that produce storage economies ... , but rather ones in which marvels are produced by profligate use of capacity".

We can identify a number of models that occupy the middle ground on the continuum between these two extremes described above. Many of these models represent a compromise solution to the two opposing economy principles. In general they include words in the lexicon either as full forms or as morphemes (or both) depending upon specific criteria (e.g. word frequency, derivational versus inflectional affixes, productive versus unproductive affixes, prefix versus suffix, etc.). For example, one model of language production (Stemberger and MacWhinney 1988) appeals to two criteria, regularity and frequency, to determine whether inflected words are listed or represented by stem and rules. Irregular forms are all stored whereas most regular forms are computed by rule with the exception of high frequency items which are stored. This model produces savings in storage by decomposing the majority of regularly inflected forms and savings in processing by storing the high frequency forms that would otherwise have to be computed most often.

This discussion should make it clear that the two principles do not give a sufficient basis for preferring one model over another. Nonetheless, they provide some helpful guidelines when applied to specific contrasting languages like English and Turkish. These languages differ considerably in productivity and in the regularity of their morphological rules. As Hankamer's computations show, an agglutinative language like Turkish has many (possible) word forms so that a considerably larger storage savings can be made than in English. Moreover, the morphological rule system is much more productive and regular in Turkish than in English suggesting that a parser would be much more effective for the former. The major differences in the morphological structure across languages make it dangerous to generalize about processing based on one language or even one family of lan-

guages. Unfortunately, psycholinguistic research has been restricted to a handful of similar languages — English, Dutch, and French — which show minor structural differences and relatively impoverished morphological structure. More research is clearly required with speakers of morphologically richer languages (see also Hankamer 1989) to evaluate these principles.

3. THE PRODUCTIVITY CONSTRAINT AND WORD RECOGNITION MODELS

Any model of word recognition should be able to explain the processing of novel forms. We encounter them often and we seem to be able to process them easily. Nonetheless, psycholinguistic models of word recognition have paid little attention to the issue of productivity. This indifference towards productivity can be seen in the models characterizing the end-points of our continuum. For example, although the prefix stripping model of Taft obligatorily parses the input and therefore in principle could handle morphological productivity, it does not address the issue. When the parser encounters a new derivationally complex word, it can strip off its affix(es) and locate the stem, but it has no means of processing the input further. The major problem is that this model does not incorporate information (i.e. rules) that specify how affixes and stems may be combined, what combinations are permissible in the language, and how the meaning of the whole word may be computed given the meaning of stem and affix. This is presumably because this model was developed to explain lexical decision performance — that is, to distinguish actual words from all other input strings (e.g. potential words, pseudo-nonwords, and illegal nonwords). At the other extreme, full listing models are by definition incapable of dealing directly with novel forms which of course cannot be listed. Proponents of these models, nonetheless, acknowledge that novel forms must be processed in some fashion. They generally postulate a back-up or fall-back procedure which comes into play when the direct access route fails (Butterworth 1983).

3.1. *The Augmented Addressed Morphology (AAM) model*

One model that deals with productivity is the Augmented Addressed Morphology (AAM) model (Caramazza, Laudanna, and Romani, 1988; Laudanna and Burani, 1985). This model assumes the existence of two routes by which a letter string input can be processed: one involving direct access and the other involving morphological decomposition. The input is assumed to activate simultaneously both whole-word representations (where available — that is, for known words) and the morphemes that comprise them. So, for example, *walked* will activate the full form ((WALKED)), its component morphemes ((WALK), (-ED)), as well as orthographically similar forms (e.g., (TALKED)). The orthographic representation that first reaches a preset threshold will activate its corresponding lexical entry and be recognized. Here we have a race, but actually the race is fixed. The model stipulates that the whole-word representations reach their threshold before

the morphological units, and the direct route always 'wins the race' for word inputs.

In the AAM-model, the slower decomposition route serves essentially in the processing of nonwords and the comprehension of novel forms for which there is no whole word entry. This route has been submitted to various empirical tests by Caramazza and his colleagues. In their experiments, they have shown that the time to reject a nonword in a lexical decision task depends upon the morphological structure of the nonwords. They contrasted lexical decision latencies to several different types of nonwords: legal morphologically complex nonwords, illegal morphological complex nonwords and finally matching nonwords. The descending order of reaction times (RTs) obtained for these different nonword types is taken by the authors to support their model. However, their use of nonword experimental stimuli to draw conclusions about the processing of words has been criticized by Henderson (1985, 1986) who advised caution in making this kind of inference. Caramazza *et al.* (1988: 325) react against what they call "... the arbitrary and implausible assumption that the cognitive mechanisms engaged in the processing of words and nonwords respectively, are completely disjunctive." However, the AAM model appears to assume such disjunctive processing implicitly since it allows no overlap in the temporal distribution of the processing times of two respective routes for words and nonwords. In this sense the decomposition route must be seen as a back-up process for the processing of novel words and nonwords.

3.2. Race models

We turn now to other proposals in which the processing of novel and productive forms is less distinct from that of other words. Like the AAM model, these assume dual routes, but they allow some temporal overlap between the routes. Before we consider some of these models in more detail, it is important to insist on the differences between models for producing and understanding novel forms. Although both assume a race between the direct access and rule-based routes (and in some models a third analogy-based route), the competitors in the race are quite different. In production models such as that of Anshen and Aronoff (1988), two different word forms compete and the winner is the produced output. These models explain some distributional facts by having the winner block or prevent the competing word with a rival affix from being produced. For example, high frequency irregular forms (e.g. plurals) are retrieved quickly via the direct access route and prevent the regular rule-based forms from coming into the lexicon and replacing them.

The situation is different in language comprehension where only one form is being processed at a time, and the two routes compete for the recognition of this form. We will be concerned here only with the problem of comprehension. According to race models of morphological processing, some or even all words have both full and decomposed entries and are accessed by the direct or the parsing routes, respectively. Although processing systems

based on this assumption are redundant and thus clearly go against the spirit of both economy principles, they can be motivated for reasons of efficiency as we will see below. Several questions arise in the construction of models assuming dual access routes and representations. First, it must be specified which words receive double representation and are processed via two routes. Second, the factors that determine the speed with which each route can complete its analysis must be identified. The required processing time of a route is generally based upon specific properties of the stimuli (e.g. word frequency, regularity, transparency, etc.). Finally, the odds, or better the probability, that a given route wins the race for the recognition of a particular form must be given. In what follows we examine how Baayen's race model has dealt with these questions and in particular how morphological productivity is assumed to influence the outcome of the race.

4. PRODUCTIVITY AND LEXICAL PROCESSING ACCORDING TO BAAYEN

In the psycholinguistic section of his paper, Baayen sketches a race model in which morphological productivity plays an important role in determining lexical processing. Baayen uses the race model architecture to model both the production and recognition of novel words and words with productive affixes. For production, he attempts to explain some distributional facts and experimental results concerning combinations of affixes that have been discussed previously by Anshen and Aronoff (1988). We will focus our attention here on the receptive end of processing. Before considering the details of the model, we briefly consider the quantitative measure of productivity that Baayen developed.

4.1. Baayen's measure of productivity

An important contribution of Baayen's work (1989, this volume) is his new measure of morphological productivity, P . This quantitative measure provides us with an objective, statistical measure of productivity for every affix. It is computed as follows. All words in a large text corpus containing the specific affix under scrutiny are counted. Thus, the number of tokens, N , in that corpus is computed. Furthermore, the number of words that contain that affix and occur exactly once (so called hapaxes) in the corpus is also counted. Baayen's P is the computed by dividing the number of hapaxes, n_1 , by N , the number of tokens: $P = n_1/N$. P gives us a measure of the probability that new types with that particular affix will be encountered when the size of the corpus is increased. To test whether a certain affix is truly productive it can be tested against the P value of morphologically simplex forms. Moreover, different affixes can be compared with respect to their productivity measures and this difference can be statistically tested. Thus, Baayen and Lieber (1991) have exploited this measure to compare the productivity of different derivational affixes in both Dutch and English. A comparison of the productivity measures of well-known rival affixes like 'ness' and 'ity' produce differ-

ences that are consistent with natives' intuitions and linguists' analyses. For a linguistic discussion of productivity we refer the reader to the commentary of van Marle (this volume).

4.2. Baayen's Race Model

Baayen's Race Model assumes that all morphologically complex words have both a full listing and a morphologically decomposed entry and thus can be recognized in principle by either the direct or the parsing route. The time taken to process a word with the direct route depends upon the token frequency of the target word. A word's token frequency is taken to provide a measure of its resting activation level, along the lines of the approach taken in interaction activation models (McClelland and Rumelhart 1981). The factors determining the time taken by the parsing route are not specified. These two routes start simultaneously and race in parallel, with the one reaching completion first giving its output. Although the direct route is generally quicker than that involving parsing, the two overlap temporally to a limited extent. Consequently, low frequency forms can be recognized via either route. Thus, the model differs from the AAM model in that the outcome of the race between the direct access to the full form and access via morphemes is not completely fixed.

4.3. Morphological productivity in the model

A major objective of Baayen's proposal is to incorporate morphological productivity into a model so that productive forms are parsed and unproductive forms are not. Baayen appeals to his observation that there is a relation between the frequency distribution of morphologically complex word forms and the productivity of the affixes composing these word forms: words with unproductive affixes tend to be more frequent than those with productive affixes. Given this relation, it follows that, on average, words with unproductive affixes will be recognized via the direct access route and those with productive affixes will be parsed — at least if they are low enough in their frequency.

It is important to note that Baayen's proposal exploits word token frequency to link the morphological productivity of a particular form and the route by which it is recognized. This indirect approach is not without its problems. The model may perform as desired on average over the entire vocabulary, but not for specific words. Thus, unless productivity is specified in some more explicit fashion, it would presumably recognize a productive and an unproductive word of equal frequency in the same manner, and consequently would parse low frequency unproductive words.

Baayen would obviously prefer a more direct way of expressing the degree of productivity in term of some processing mechanism that predicts differences in recognition routes between productive and unproductive forms. Baayen (1989, this volume) considers several alternative mechanisms, but finds none that is satisfactory. He rejects the idea of associating with each

affix its *P* value for logical reasons. To decide whether a morphologically complex word should be parsed or not, its *P* value would have to be identified. However, to do so, the affix would already have to have been parsed. He also rejects another approach in which the degree of productivity is encoded in the activation levels of affixal units or lexical entries themselves. He points out that this solution is problematic since it loses the critical information concerning the relationship between affix frequency and productivity. Two affixes — one productive and the other unproductive — can attain the same activation level in two different ways — one from many low frequency (presumably productive words) and the other from a single high frequency word. Furthermore, a few high frequency words — with productive or unproductive affixes — would swamp the affixal frequency counter.

In the absence of any satisfying way of integrating his quantitative measure of productivity into a psycholinguistic model of word recognition, Baayen resorts to exploiting the indirect relation between this measure and word token frequency. Clearly, word frequency is the most important factor determining word recognition. Nonetheless, it is probably not correct to use word token frequency to explain differences in the processing of productive and unproductive words. There are other *distributional properties* of words like the type and token frequencies of their stems and affixes that may be more appropriate. In any event, this issue cannot be resolved with the analysis of lexical corpora, but must be addressed experimentally with native listeners.

It is important to point out that factors other than these distributional ones play an important — and probably more important — role in determining the recognition of morphologically complex words. These factors concern the *inherent* properties of words, that is, the phonological and semantic make-up of these words and their morphological parts. Unfortunately Baayen neglects these factors in his discussion of productivity and lexical processing. It is to these issues that we now turn our attention.

4.4. Inherent lexical factors

Both phonological and semantic factors influence how easily a (novel or familiar) morphologically complex word can be analyzed. We begin by considering the role played by the phonological attributes of a word. A first important attribute is *phonological transparency* which refers to how similar a derived word is to its base in terms of form (e.g., vowel quality, stress pattern). The addition of certain affixes leads to opaque forms which differ from their bases (*curious* — *curiosity*), whereas the addition of other affixes produces transparent forms with the bases essentially unmodified (*curious* — *curiousness*). The words with productive affixes tend to be phonologically transparent and those with unproductive affixes are often opaque. There is another related phonological property that is also correlated with productivity. As Aronoff (1976) has shown, the phonological shape of bases with unproductive affixes can be idiosyncratic and not predictable. Aronoff gives the example of words containing the suffix *-ous* which is dropped in some cases (*various* → *variety*) and not in others (*curious* → *curiosity*) when the

unproductive affix *-ity* is added. The uncertainty resulting from a lexically governed rule complicates the speaker's (and also the listener's) task in producing (and comprehending) a novel form based on these affixes. Baayen mentions another phonological difference between productive and unproductive affixes. He gives an example of rival affixes where the unproductive one is more ambiguous or confusable with other forms (i.e., affixes) than the productive one. In sum, all of these differences in the phonological properties of word forms made up of productive and unproductive affixes suggest that the former should be easier to decompose and produce.

Cutler (1980) has conducted a number of experiments showing that this indeed is the case. She investigated the role of phonological transparency in experiments comparing preferences of speakers and listeners for nonce formations created with rival affixes: word boundary affixes ($\#$) and formative boundary affixes (+). When asked to judge the acceptability of neologisms, subjects preferred those forms constructed with the productive affixes. However, this preference disappeared when the phonological transparency of the productive and unproductive forms was maintained constant. Thus, only the opaque unproductive words containing a shift in stress or a change in the vowel received a disfavorable judgement. Cutler (1981) goes on to suggest that listeners' judgments do not depend upon the transparency of the entire stem, but only upon that initial part that gives a unique left-to-right specification of the stem. She concludes from her experiments that the preference of subjects in the experiments depends critically upon whether the part of the stem in the derived form that allows its unique identification remains transparent.

Semantic factors have not received as much experimental attention as phonological ones, but may be no less important. Aronoff (1976) points to differences in *semantic coherence* between words formed with productive and unproductive affixes. He defines a word formation rule as being semantically coherent when it is possible to predict the meaning of the word formed by the rule. He contrasts the semantic coherence of the two suffixes *-ity* and *-ness*. For the former there are many more idiosyncratic semantic interpretations. Aronoff concludes that more productive affixes lead to the semantically more coherent or transparent forms.

Semantic coherence and phonological transparency may go hand in hand as is illustrated by the two rival affixes just described. Furthermore, these two inherent properties of words and their component parts are also closely linked to the productivity of the implicated word formation process. In modeling the processes underlying the recognition of morphologically complex words and neologisms, the precise nature of this link must be made explicit. We want to claim that the inherent properties of words resulting from different word formation processes determine the productivity of these processes. Further, this relationship should be expressed in models of word recognition. Experimental evidence cited above shows that speakers favor novel forms which are based upon productive affixes only when these are phonologically transparent and semantically coherent. After all, these are also easier for the listener to understand. Consequently, the rules generating

these more transparent forms will be favored and thus more productive. However, the distributional properties of words may also have an effect upon productivity. As forms with productive affixes are produced or understood correctly more often, the familiarity of the affix increases and so should its ease of processing. As a result, distributional properties of words may also contribute to determine the morphological productivity. This suggests that the processing consequences both of the inherent properties of morphologically complex words and the productivity of their affixes should be captured in a model of word recognition. In what follows we attempt to show one way in which this can be accomplished.

5. THE MORPHOLOGICAL RACE MODEL (MRM)

In this section we extend the proposal of Baayen and consider the factors that influence the parsing route. However, our objective is not to present a fully elaborated model. We will remain neutral with respect to the modality (visual or auditory) of the processing and the exact internal structure and mechanisms of the parser. Our intent is to offer an indication of how the productivity constraint can be applied to a word recognition model more directly. Furthermore, our morphological race model points to some interesting directions that further empirical research, especially cross-linguistic, could take. In presenting this model, we address the questions that any race model must deal with.

5.1. *Who's in the race?*

We assume, just as Baayen and others do, that there are two routes, a direct route and one involving morphological parsing. The direct route employs access representations of the full word, and the parsing route employs access representations of stems and affixes, similarly to Caramazza *et al.* (1988). Both processes run in parallel, and the faster route wins the race. The time to recognize a word via either route is a stochastic variable with some overlap in the temporal distribution of these two routes. This means that for certain morphologically complex words, both routes have a chance at winning the race.

5.2. *What determines the time taken by each route?*

5.2.1. *Direct route*

The time taken for a word to be recognized via the direct route is influenced by the token frequency of this word. The more often a form is encountered, the higher the resting activation level of its access representation becomes. The higher resting activation level of a high frequency word form gives it a 'headstart' as compared with less frequent word forms. The access representation of a frequently occurring word will require less stimulus information to reach its threshold and will be recognized more quickly via the direct route.

5.2.2. Morphological parsing route

The time taken for the parsing route to recognize a word depends on both the inherent (i.e. transparency) and the distributional (i.e. frequency) properties of a word. First, the inherent properties of a morphologically complex word determine how easily and quickly it can be parsed. Both phonological and semantic factors play a role here as we showed in Section 4.4. We assume that morphologically complex word forms that are both phonologically and semantically transparent take less time to parse than words that are less transparent at either level. Phonological transparency influences the time taken both to identify the individual morphemes and to combine them. The semantic coherence of a form affects the time taken to integrate the meanings of its stem and affixes. Second, we assume that the time taken to parse a word depends on the resting activation levels of its stem and affix(es). A word whose stem and affixes have a high resting level will have a 'headstart' in the parsing against other words. The resting activation levels of the access representations of the stem and affix will be increased *only* when the parsing route wins the race and produces a *successful* parse. A successful parse is one in which the analysis of the stem and its affix(es) leads to a meaningful interpretation. A parse involves first dividing the input into its morphological parts, and then recombining the syntactic and semantic properties of these parts into a coherent whole. If this process is completed before the direct route has delivered its meaning representation then we can speak of a successful parse.

5.3. What determines the winner of the race?

Our race model should in principle give both a synchronic and a diachronic answer to this question. From a synchronic perspective, the model must be able to determine the probability that a given route completes the analysis of a particular form first. Diachronically, it must specify how the processing of a particular form evolves over time with successive exposures. We will start with a diachronic perspective.

5.3.1. A diachronic picture

The model must express the evolution or progression in the way in which morphologically complex words are recognized across successive exposures. The morphological parsing route is initially responsible for the processing of novel morphologically complex forms. However, after (many) more exposures to the word, the direct route takes charge. Ultimately, high frequency words are assumed to be recognized primarily via the direct route. One of the objectives of the model is to account for this evolution from the parsing to the direct route and to show how it varies as a function of the morphological properties of the word.

To characterize the evolution in the recognition of morphologically complex words, we begin by considering the processing of a novel form or a neologism. When confronted with such a form, the listener's most reasonable strategy is to attempt to parse it. The probability that the parsing analysis will

succeed is a function of the inherent properties (i.e. transparency) of the word and the distributional properties of the morphologically related words. Novel transparent words whose component morphemes are already listed in the lexicon should be analyzed and recognized relatively easily. The situation is quite different for morphologically simple or opaque words for which the parsing route should fail. These words must be entered directly into the lexicon as full forms.

Every time the listener parses a particular form successfully, the activation levels of its constituent morphemes increases. If this were the only mechanism assumed in the model, the parsing route would always win the race against the direct route. For the direct route to become a serious contender and ultimately even to dominate the race for high frequency words, we need to make two further assumptions. First, we must assume that the full form obtains its own representation even though the word is successfully recognized via the parsing route. The idea here is simply that a full representation is created after the first parse or at least after some limited number of exposures. Second, we need to assume that the resting level of activation of the full form increases more after successful recognition than the activation levels of the component morphemes do after successful parsing. In the model, the direct route will win on some occasions, and gradually there will be a shift so that the direct route becomes faster than the parsing route. The number of exposures at which this shift takes place depends upon the properties (e.g. transparency, productivity) of the word.

The resting activation levels of morpheme and word units do not just increase, they can also decay over time when these units are not encountered (or successfully parsed) for some time. The representation of the constituent morphemes of high frequency words will decay since they are rarely parsed successfully. As a consequence, these morphemes might even disappear from the lexicon — unless of course they receive some activation from morphologically related words. At the other frequency extreme, the full form representations of low frequency words will tend to decay more than those of their morpheme parts. This is because the resting activation levels of the morphemes are influenced by other morphologically related words (i.e. those sharing the stem or affixes). The chances that the parsing route wins the race for these words is thus improved.

5.3.2. A synchronic picture

Several factors determine which route wins the race for a given presentation of a particular word. Word token frequency is the most important factor in determining the winner of the race. Word forms with a high surface frequency will generally be recognized by the direct route, irrespective of their morphological structure (i.e. whether they contain productive or unproductive affixes). This is because frequent words have a headstart via the direct access route given their increased resting activation level.

For the words of medium to low frequency the outcome of the race is less certain and depends upon other factors including the parsability of the word and the cumulative frequency of its stem and affixes. Transparent morpho-

logically complex words are easier to parse and thus stand a greater chance at being analyzed by this route. The cumulative frequencies of a word (the combined frequency of all the words containing a shared stem) as well as the affix frequency (the combined frequency of words with containing this affix) also contribute to determining the speed of the parsing route. However, these two frequency values do not reflect the resting activation levels of the stem and affixes exactly since the activation levels are increased only when the parsing route wins the race. Hence, high frequency words — which could in principle contribute the most to the activation level of their component morphemes — do not because they are recognized via the direct route.

5.4. Morphological productivity and the MR model

The MR model predicts that the parsing route has the greatest chance of winning the race for words that are transparent and low in frequency. It is here that the parsing route is the fastest and the direct route the slowest. These inherent and distributional properties are precisely those of words formed with productive affixes. The productivity of affixes is strongly correlated with the degree of phonological and semantic transparency of the words that they make up. Furthermore, as Baayen has shown, the frequency distribution of words formed with productive affixes favors their recognition by the morphological parser. Words with a productive affix will tend to be of medium to low frequency. The parsing route has the best chance of winning the race for words in this frequency range because the resting level of activation of the full form is relatively low. Thus, word forms with a productive affix are more likely to be parsed successfully than words with unproductive affixes. Low frequency word forms with an unproductive affix present an interesting case. What is critical in determining whether the parser has any chance of winning the race is their degree of transparency. If they are fully opaque the parser cannot complete its analysis, and the direct route wins the race by default.

As a result of being parsed successfully, productive forms will have stem and affix representations with higher resting activation levels than word forms with a less productive affix. The activation level of an affix thus represents the relative ease with which a form with this affix is parsed and is positively correlated with the productivity of the affix in question. It is important to remember that the activation level of a given affix is determined only by the number of successful parses of words with that affix, and *not* by the number of times a word form with this affix has occurred. The problem of saturating the frequency counter of a certain affix with a single high frequency word form which we mentioned in Section 3.2, is solved by using the criterion of successful parsing. In this way, Baayen's *P* measure is represented within our model indirectly by the resting activation levels of the access representations of affixes and is a *consequence* of successful parsing. It is important to remember, however, that it is the transparency of the form that determines the performance of the parsing route.

5.5. MR model and empirical predictions

The model makes a number of interesting predictions concerning the recognition of morphologically complex words. Many of these have to do with the way in which a word's frequency (both token and cumulative) interacts with its transparency to determine the winning route. In general, the model predicts that the clearest effects of morphological structure will emerge for low frequency words. The complicated interplay between transparency and frequency may account for the absence of an empirical consensus on the role of morphological structure in word recognition (see Henderson 1985, for an overview). This state of affairs could in part be due to the fact that the experimental studies have used words with different frequency ranges and generally have not manipulated or controlled the transparency or productivity of the stimuli. In what follows we consider a few of the predictions of the model.

5.5.1. Recognition speed and productivity

The model predicts that low frequency words with productive affixes will be recognized faster than both words containing unproductive affixes (leading to opaque forms) and morphologically simple words when surface and cumulative frequency are held constant. This prediction is the simple consequence of having two distinct processing routes. It is a well-known property of race models that the overall speed of performance is faster when two routes are involved in the race than just one alone. The amount of so-called 'statistical facilitation' (Raab 1962) depends upon the overlap and shape of the reaction time (RT) distributions of the two routes. For simplex words and words with unproductive affixes the race will be mainly won by the direct route, that is, there is not much overlap in the distributions. For transparent words with productive affixes the amount of overlap will in general be larger. As a consequence, the model makes the counterintuitive prediction that morphologically complex (but transparent) words will be recognized faster than morphologically simple words. We can speculate that this gain in processing speed in a dual route model may compensate for the additional storage costs associated with including both the full and decomposed representations, and for the additional processing costs associated with pursuing two different routes in parallel.

5.5.2. Cumulative frequency effects

It has been demonstrated in several experimental studies (Bradley 1981; Burani and Caramazza 1987; Colé, Beauvillain and Segui 1989) that the recognition of a morphologically complex word depends not only on its surface frequency but also on the frequency of the other words in its morphological family — i.e. sharing the same stem. Any model of word recognition must be able to explain this cumulative root frequency effect.

The MR model makes specific predictions about the cumulative frequency effect. It assumes that this effect arises only when the parsing route wins the race. The strength of this effect is assumed to depend upon both the inherent

and distributional properties of the target and those of the morphologically related words. We expect cumulative root frequency effects to emerge most clearly for lower frequency words that are transparent. For these words, the parsing route stands the best chance against the direct route, and the processing consequences of the more highly activated stem representations can be detected. The largest contribution to the stem's activation — and thus to the cumulative frequency effect — results from the recognition of the isolated base form. The size of this contribution is a direct function of the frequency of the free base form since this form is necessarily recognized via the direct route. However, the properties of the other morphologically related words are also important. For a cumulative frequency effect to emerge, these should be of lower frequency and transparent. Since related morphologically complex words of high frequency will generally be recognized via the direct route, the resting level of activation of the stem will not be affected. In contrast, since the parser is assumed to recognize the lower frequency related words on some occasions, the resting activation level of the stem will be increased. We see thus that this simple model makes some testable predictions about the conditions in which the cumulative frequency effect should be obtained.

5.6. *Cross-language differences*

One might wonder why we have placed so much emphasis upon the parsing route in our discussion of morphological processing since the direct access route presumably wins the race for most English words. However, if we remove our linguistic blinders and consider languages other than those languages that commonly have been the object of psycholinguistic study (e.g. English, Dutch, French, etc.), we see that the relative importance of the direct and parsing routes may well reverse.

There are many languages whose morphology is highly productive. For example, in an agglutinative language like Turkish, the listener is constantly confronted with novel forms. Since our model is meant to handle a wide range of languages, we might ask how it would deal with this type of language. Turkish is not only morphologically productive, but also phonologically transparent. Thus, we expect that the parser will win the race in the analysis of most morphologically complex Turkish word forms. Indeed, many word forms will be analyzed by the parsing route because they are made up of morphemic combinations that occur rarely. However, it is possible that combinations of root and affixes that a listener encounters frequently could get a separate access representation. Consequently, a single word form might be recognized through the cooperative efforts of the direct route and the parser. The frequently co-occurring root plus affixes would be recognized by the direct route, and the rest of the word by the parser that combines the results of the direct route with the remaining morphemes to be parsed.

As Anderson (1988) has pointed out, Turkish represents a parade case for agglutinative languages in that the affixes are relatively transparent and segmentable. Not all languages with agglutinative morphologies have this

property. For example, Finnish is a language with a productive morphology but with word forms whose underlying morphological structure is obscured by a complex system of phonological rules. The absence of transparency together with the high productivity of the language creates a serious dilemma for any parser. On the one hand, the low surface frequency and the high morphological complexity of Finnish word forms would call for a parsing solution. On the other hand, the opacity of the surface forms makes recovering the underlying morphological structure a very complex enterprise for the parser (cf. Anderson 1988). Finnish listeners appear to have found an efficient solution for handling this paradoxical situation, since they are not slower in recognizing words than listeners of English. If this solution involves parsing, then the notion of phonological transparency that we have endorsed may not be as decisive in determining the route taken as we have suggested. Clearly, more research is required to understand the nature of this parsing and the type of underlying access representations that the complex morpho-phonological processes map the sensory input onto.

6. CONCLUSIONS

In this paper we first examined two constraints that have been used to motivate the morphological organization of word recognition models. These are the complementary principles concerned with the economy of storage and the economy of processing. We concluded that it is premature to construct a model on the basis of either of these constraints in the absence of more psycholinguistic data. We subsequently discussed another type of constraint, the productivity constraint. We have argued that a model must be able to account for the listener's ability to parse and interpret novel morphologically complex word forms. Most current models deal with novel forms by means of a secondary or back-up procedure (see Aitchison 1987 for an illustration of such a 'back-up store' and 'lexical tool-kit'). We have argued here that the parser should not be seen as a back-up procedure that is reserved only for novel words. Rather we suggest that it is integrated more directly in the lexical processing system and plays an important role in the recognition of both novel and known words. Research with languages processing a rich morphological structure (like Turkish) should allow experimental confirmation of these claims.

Baayen's (this volume) race model represents an important attempt to deal explicitly with morphological productivity. This model includes a direct route and a parsing route that operate in parallel. To have the model parse the words with productive affixes, Baayen exploits the relation he observed between word token frequency and morphological productivity. Baayen's approach is clearly incomplete since it identifies one factor (i.e., frequency) determining the speed of the direct route, but fails to specify the factors that influence the parsing route.

In extending Baayen's model, we have been more specific concerning the factors determining the contribution of the parsing route. The MR model does not exploit the relation between productivity and word frequency as

Baayen does, but uses the link between morphological productivity and the phonological and semantic transparency of word forms. In this model the winner of the race is determined by surface frequency and parsability. The probability that the parsing route wins the race is highest for transparent low frequency word forms. Typically these will be word forms containing productive affixes. The direct route will win the race for high frequency word forms and those word forms that are problematic for the parser, for example, opaque word forms containing unproductive affixes.

The MR model is presented here only in its bare skeletal structure. Clearly, it needs to be fleshed out considerably. One step in this direction could be made by implementing the model on a computer. A computer model would necessarily be more explicit in its structure and parameter space. Computer simulations would be useful to study the way in which various model parameters (e.g. increases in the resting activation levels of full words or their morphemic parts after recognition via the direct or parsing routes) determine the outcome of the race diachronically. Even more important in the longer term is illuminating (perhaps also through computer implementation) the internal workings of the human morphological parser which at present is nothing more than a black-box in most models.

NOTE

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