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Syllabification in Speech Production: Evaluation of WEAVER

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Models of speech production differ in their claims about syllabification. In a memory-based approach such as that advanced by Dell (1986, 1988), the syllable structure of each word is stored in the mental lexicon. In contrast, according to a rule-based approach, planning of speech involves the assignment of syllable positions to segments after they have been retrieved for a word from memory (e.g. Levelt, 1992). Here, a case is made for the rule-based approach of the WEAVER model of speech production (Roelofs, 1994, in press a). First, I argue that cross-morpheme and cross-word syllabification point to the need to deal with flexibility of syllable membership and therefore pose difficulty to a memory-based approach but not to WEAVER. Secondly, I review empirical support for the specific form of syllabification realised in WEAVER. Thirdly, I report a new experiment on syllabification, which supports WEAVER rather than Dell's model. Finally, the issue of resyllabification is discussed.

INTRODUCTION

In planning utterances, speakers call on many facets of their stored knowledge about words, including their meaning, syntactic properties, morphological composition and phonological structure. Lexical access is the process by which this information about words is retrieved from memory so as to construct articulatory programs for concepts to be verbally expressed. The access to a single word is achieved in two major steps: lemma retrieval and word-form encoding (e.g. Butterworth, 1989; Dell, 1986; Garrett, 1975, 1988; Kempen & Huijbers, 1983; Kempen & Hoenkamp, 1987; Levelt, 1989, 1992; Roelofs, 1992a,b, 1993). In lemma retrieval, a lexical concept is used to retrieve the lemma of a corresponding word from memory. A lemma, as I use the term in this paper, represents the syntactic properties of a word. For

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example, the lemma of the Dutch word *juweel* (*gem*) says that it is a noun and that its grammatical gender is neuter. In word-form encoding, the morphophonological properties of the word are retrieved from memory to construct an articulatory program. It is generally assumed that this process involves the recovery or assignment of a syllable structure.

Theories of the encoding of word forms differ in their claims about syllabification. On the one hand, "memory-based" theories assume that the syllable structure of each word is stored in the mental lexicon. For example, on this view, the memory representation of *juweel* would specify something like /onset j/ and /nucleus y/ for the first syllable, and /onset w/, /nucleus e/ and /coda l/ for the second syllable (e.g. Levelt, 1989; Shattuck-Hufnagel, 1979). This view of syllabification is held by the classical computational model of form encoding in speech production, the model of Dell (1986, 1988). On the other hand, "rule-based" theories assume that memory does not contain such ready-made syllable structures for words. Instead, word-form encoding comprises a process that assigns syllable positions to segments after they have been retrieved from memory (e.g. Béland, Caplan, & Nespoulous, 1990; Levelt, 1992; Levelt & Wheeldon, 1994). For example, the memory representation of *juweel* says that its final segment is /l/ but does not specify the syllable position of this segment. Whether the /l/ occupies an onset or a coda position will only be determined when the word is actually made part of an utterance.

Theories assign different roles to metrical structure in syllabification. Metrical structures specify at least the number of syllables and the stress pattern—if they represent nothing else they are minimal. Theories differ in whether metrical structure is computed on-line (e.g. Béland et al., 1990) or stored (Levelt, 1992). Stored metrical structures may be minimal (Roelofs, 1994, in press a) or may represent the precise CV structure of the syllables (Dell, 1988). According to Levelt (1992), syllable structure is computed on-line by associating retrieved segments with retrieved metrical structures. This view of syllabification is realised in a specific manner in the WEAVER (Wordform Encoding by Activation and VERification) model of form encoding in speech production (Roelofs, 1994, in press a). According to WEAVER, a principle of economy holds in that metrical structures are stored for some, but not all, words.

In this paper, I make a case for the view on syllabification held by WEAVER. The paper is organised as follows. First, I discuss how syllabification is treated in two computational models in the literature. In the discussion of a memory-based approach, I focus on the model of Dell (1986, 1988) because this model has been more explicit about syllabification than other models of this kind. Furthermore, aspects of the model have been explored through simulation. I argue that Dell's model has difficulty with certain aspects of syllabification; in particular, syllabification across morpheme boundaries and across word boundaries. Furthermore, I explore how these problems might be solved within the framework of this model. In the discussion of a rule-based approach, I focus on the WEAVER model of word-form encoding. I will show how WEAVER handles syllabification across morpheme boundaries and word boundaries. Next, I review the outcomes of two series of experiments that support WEAVER's specific view on syllabification. Then I report a new experiment that contrasts Dell's model and WEAVER. Finally, I discuss the issue of resyllabification.

THEORETICAL POSITIONS

To set the stage, I discuss the role of word-form encoding in the process of lexical access in speech production. Three major types of processes underlie speaking: conceptualisation, formulation and articulation (e.g. Caplan, 1992; Garrett, 1975; Kempen & Hoenkamp, 1987; Levelt, 1989). Conceptualisation processes generate so-called messages; that is, conceptual structures to be verbally expressed. In the view held by WEAVER, messages are specified in terms of lexical concepts and their relationships. Formulation processes take the message, access appropriate words for the lexical concepts (i.e. lemma retrieval and word-form encoding) and build a syntactic structure—in the case of sentence production—and a morphophonological structure. The result is an articulatory program for the utterance. Finally, articulation processes execute the articulatory program, which results in overt speech.

As indicated, lexical access consists of two major steps, lemma retrieval and word-form encoding, corresponding to the formulation stages of syntactic encoding and morphophonological encoding, respectively. In lemma retrieval, a target lexical concept is used to retrieve the lemma of a corresponding word from memory. Lemmas represent the syntactic properties of words. Lemma retrieval makes these properties available for syntactic encoding processes. In word-form encoding, the morphophonological properties of the word are retrieved from memory to construct an articulatory program. Below, I describe a widely accepted psycholinguistic view on lexical access (cf. Levelt, 1989, 1992), which has been adopted by WEAVER. The encoding stages are uncontroversial, but the assumptions about the computations and their output may differ between models.

Assume that a Dutch speaker wants to name a gem. Lexical access consists of mapping the lexical concept GEM(X) onto the articulatory program for *juweel*. The lemma retriever takes GEM(X) and outputs the lemma of *juweel*. To derive the singular form [jy.'wel] instead of the plural form [jy.'we.lə], the word's number has to be specified. The lemma plus this abstract morphosyntactic number parameter are then input to word-form encoding.

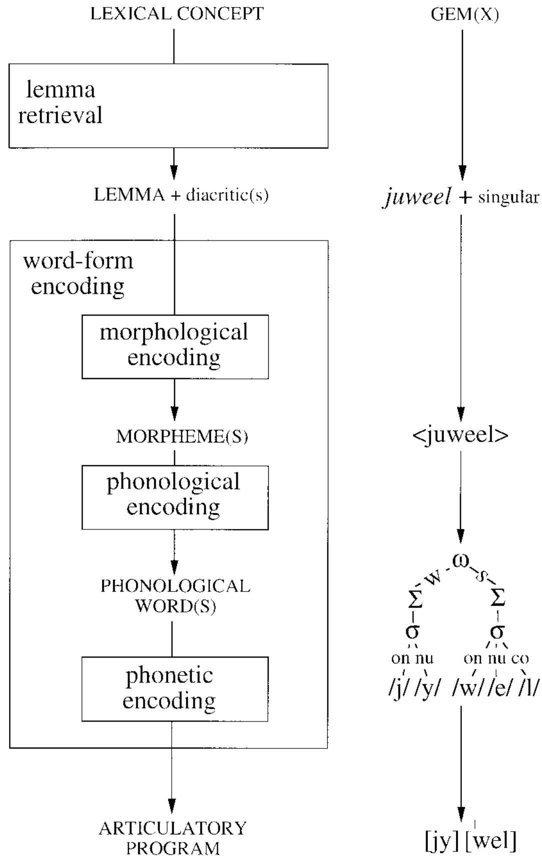

FIG. 1. Lexical access in speech production: Lemma retrieval and word-form encoding (cf. the WEAVER model; Roelofs, 1994, in press a).

The articulatory program is derived in three major steps (cf. Dell, 1986; Levelt, 1989, 1992): morphological encoding, phonological encoding and phonetic encoding (see Fig. 1). The morphological encoder takes the lemma of *juweel* plus the parameter singular and produces the stem morpheme <juweel>. This first stage thus concerns what is traditionally called the "syntax–morphology interface" (e.g. Spencer, 1991). The phonological encoder takes the stem morpheme and produces a so-called phonological word representation. This representation describes the singular form of *juweel* as a phonological word consisting of two feet, the first one metrically weak (w) and the second one strong (s). The first syllable has /j/ as onset and /y/ as nucleus; the second syllable has /w/ as onset, /e/ as nucleus and /l/ as coda. This second stage thus comprises what is traditionally called the "morphology–phonology interface" (e.g. Goldsmith, 1990). Finally, the phonetic encoder takes this phonological word representation and delivers the articulatory program, [jy.'wel]. In WEAVER, phonetic encoding involves accessing a store of learned motor programs for syllables, a so-called syllabary (Levelt & Wheeldon, 1994), and setting parameters for pitch, loudness and duration. This final encoding stage includes what is sometimes called the "post-lexical phonology" (e.g. Goldsmith, 1990).

Dell's model assumes stages of access similar to those of WEAVER described above, but there are also some important differences. For example, Dell's model does not make the claim that the output of phonological encoding is a phonological word representation and it does not assume a syllabary. How is memory organised according to the models and what is the lexical access mechanism? In particular, how is syllabification achieved?

DELL'S MEMORY-BASED APPROACH

Dell (1986) assumes that word forms are represented in a lexical network with nodes for morphemes, syllables, rimes, segments and segment clusters, and features. Figure 2 illustrates this for the Dutch word *juweel* (rimes and features are omitted to simplify the figure). The nodes for the segments and clusters are marked for syllable position. The nodes are associated with each other by weighted bidirectional connections. In phonological encoding, the activation level of a morpheme node is enhanced by giving it a jolt of activation. Activation then spreads through the network, each node sending a proportion r of its activation to its direct neighbours. Mapping a morpheme onto its segments is accomplished by selecting the highest activated segment or cluster nodes. The speaking rate determines the amount of time that is devoted to the encoding of a syllable (i.e. the time between providing the jolt of activation and segment selection). Selected nodes are inserted into slots of independently created syllable frames. The segment nodes for a syllable are selected in parallel.

In the case of multisyllabic morphemes, the links between the morpheme node and the syllable nodes are labelled for the serial position of the syllables. The syllables are serially encoded. The successive encoding of syllables is accomplished by temporarily increasing the spreading rate for one syllable and decreasing it for the others. In the encoding of a bisyllabic morpheme, activation first spreads with a rate of 1.5 r to the first syllable node and with 0.5 r to the second syllable node. After the first syllable frame has been filled, the weights are changed. Activation now spreads at a rate of 0.5 r to the first syllable node and at a rate of 1.5 r to the second syllable node. The changing of weights prevents selection of segments or clusters of the

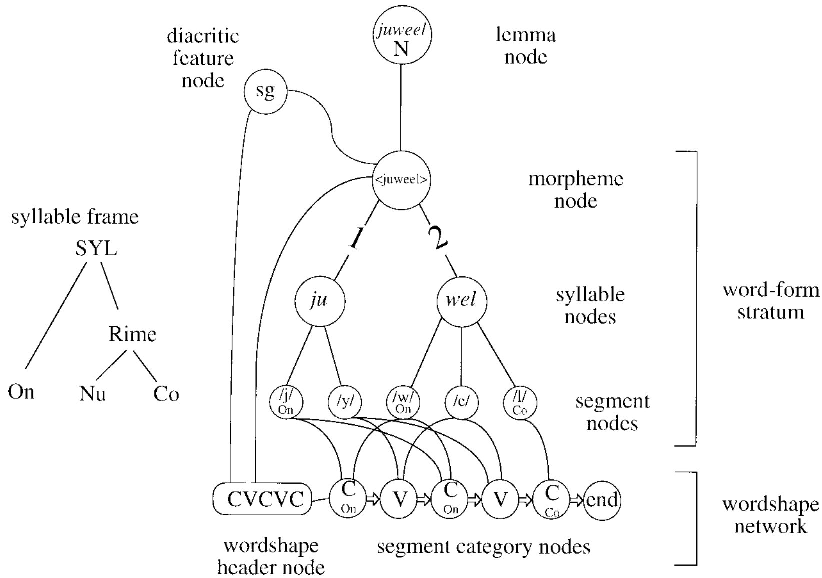

FIG. 2. Memory representation of the word form of *juweel* (*gem*) in the model of Dell (1986, 1988).

second syllable for the slots of the first syllable frame or vice versa (recall that the highest activated nodes are selected).

In a subsequent paper, Dell (1988) proposed an additional network encoding for all possible "wordshapes". Each word in the lexical network is connected to a wordshape header node that represents its CV structure. A wordshape node sequentially activates segment category nodes; that is, onset consonant (C_{On}), vowel (V) and coda consonant (C_{Co}). Each of the category nodes connects back to all possible segment nodes of its category in the lexical network. Instead of selecting in parallel nodes for the Onset, Nucleus and Coda slot of a frame, the successive activation of the segment category nodes leads to serial selection. This allows the model to account for the seriality effects in phonological encoding obtained by Meyer (1990, 1991) using the so-called implicit priming paradigm. These findings will be discussed below in the section on implicit priming.

What is the empirical support for the explicit representation of CV structure? Empirical evidence concerning CV structure is scarce (for a review, see Roelofs & Meyer, in press). Concerning speech errors, there is some evidence for a tendency towards increased similarity of the CV structures of the words involved. For example, segment additions tend to create clusters rather than singletons when the source word also has a cluster, as in "prich player" instead of "rich player" (Stemberger, 1990). The evidence is not, however, very strong. First, the CV similarity has been observed for onsets but not for nuclei. Secondly, the CV similarities are observed for some, but not all, error corpora. For example, Stemberger (1984) observed them for small corpora of German and Swedish errors, but not for an English corpus.

In terms of experimental evidence, in two priming experiments with Dutch participants, Meijer (1994) observed that word production was facilitated by spoken primes with the same CV structure as the targets relative to primes that differed in their number of consonants. However, in another experiment, this effect was not replicated. In a fourth experiment, in which primes and targets had the same or different structures of the nucleus (V or VV), no priming effect from shared CV structure was obtained.

Sevald, Dell and Cole (1995) used a repeated pronunciation task to study the representation of CV structure in English. Participants had to produce pairs of one monosyllabic and one disyllabic pseudoword as often as they could within 4 sec. The sequences were produced faster when the monosyllable had the same CV structure as the first syllable of the disyllable than when this was not the case, as in *kul-par.fen* versus *kult-par.fen*. Based on these results, Sevald et al. argued for the explicit representation of CV structure. However, as Sevald et al. measured how many targets the participants could produce within a given time period, it is difficult to establish the locus of the effect of CV structure. It could arise during the creation of the phonological representation, as Sevald et al. propose, but it could also originate during the retrieval or execution of motor programs (see Roelofs & Meyer, in press).

PROBLEMS WITH A MEMORY-BASED APPROACH

I now argue that a memory-based approach to syllabification (e.g. Dell, 1986, 1988; Houghton, 1990; Shattuck-Hufnagel, 1979) has difficulty with syllabification across morpheme boundaries and word boundaries. The problem is that a segment of one morpheme or word may be syllabified with another morpheme or word. This may occur in the production of polymorphemic words or connected speech (e.g. Chomsky & Halle, 1968; Kaisse, 1985; Levelt, 1989, 1992; Nespor & Vogel, 1986; Selkirk, 1984; Spencer, 1991). Models that rigidly store words as sequences of syllable nodes or models that store each consonant as an onset or coda have a difficult time dealing with the need for flexibility of syllable membership.

Cross-morpheme Syllabification

Consider the production of the plural form *juwelen* of the Dutch word *juweel*. The plural *juwelen* is created by adding <en> ([ə]) to the stem <juweel>. The resulting form is syllabified as $(\text{jy})_\sigma(\text{we})_\sigma(\text{lə})_\sigma$. Thus, juxtaposing <en> changes the syllabification of /l/. This segment occupies a coda position in *juweel*, syllabified as $(jy)_\sigma(wel)_\sigma$, but an onset position in *juwelen*. The syllabification across morpheme boundaries poses difficulty to models that assign segments to syllable slots on a morpheme-by-morpheme basis.

According to the model of Dell, at the morpheme level the plural of the word *juweel* would be represented by the stem node <juweel> and a node for the suffix <en>. The question is how the model handles the syllabification of the /l/ that is triggered by juxtaposing the suffix. The stem <juweel> is connected to the /coda l/ node. In Dell (1986), this node will be selected to fill the coda slot of the second syllable frame. However, for the plural form, the /l/ should be the onset of the third syllable. Thus, the /onset l/ node has to be selected for the third syllable frame. However, /onset l/ will not be activated, let alone be selected.

The wordshape headers and the sequence of category nodes proposed by Dell (1988) provide for the specification of a syllable structure that is unique to a particular combination of morphemes. A header and sequence might specify that the fifth segment of the plural form *juwelen* occupies an onset position instead of the coda position it has in *juweel*. Of course, a category node alone does not uniquely identify a segment. Recall that a category node connects back to all segments in its category. Thus, to be selected, /onset l/ must also be activated by the syllable node *len*. But what causes this node to become active? One might propose to connect the syllable node *len* to the morpheme node <juweel> as its third syllable. However, this codes the wrong information, because *len* is not the third syllable of *juweel* but the third syllable of the plural *juwelen*. Alternatively, *len* might be connected to <en> as one of its “allomorphs” and also to <juweel> without being explicitly marked as its third syllable. By not marking the syllable, it may go “unnoted” in the encoding of syllables of <juweel> in producing the singular form *juweel*. To prevent interference with the encoding of *ju* and *we* in the production of *juwelen*, the spreading rate between <juweel> and *len* should be sufficiently small. Then, activating <en> activates all its allomorphs including *len*. The /onset l/ now receives activation from <juweel>, <en> and C_{On}, so it will be the most highly activated onset node, and will be selected. For the correct production of *juwelen*, however, this is not sufficient. Note that *we* is the second syllable of *juwelen*, thus the syllable node *we* should have a labelled link to <juweel>. Therefore, we need a (yet to be specified) mechanism that selects the appropriate second syllable node, *wel* in producing singular *juweel* and *we* in producing plural *juwelen*.

In sum, cross-morpheme syllabification in Dell’s model might be achieved by connecting the critical third syllable (e.g. *len*) to both morphemes involved and connecting the syllable’s segments to category nodes (e.g. linking *len* to the stem <juweel> and the suffix <en>, and linking /onset l/

to C_{On}). Also, we have to postulate a mechanism that selects the correct second syllable node. This wordshape network solution will be empirically tested in the new experiment reported below.

The new suggestion for cross-morpheme syllabification in Dell's model may seem rather complicated and *ad hoc*. Instead, one might propose to store complex forms not in a morphologically decomposed way but as a unitary representation, for example a single "morpheme" node <juwelen> for the plural *juwelen*. There is some empirical evidence from speech errors that suggests that inflected forms of high frequency are stored in such a manner (Stemberger & MacWhinney, 1986; but see Roelofs & Meyer, in prep.). Still, the problem for items of lower frequency would remain. Furthermore, the problems in syllabification do not only arise with inflected forms but also with derivations. For example, *juwelier* (*juweller*) is syllabified as $(\text{jy})_\sigma(\text{wə})_\sigma(\text{lir})_\sigma$. Again, after juxtaposing a suffix, the /l/ of *juweel* no longer occupies a coda position but becomes a syllable onset. The option of unitary representations does not seem to be available here, because empirical evidence from speech errors (e.g. Dell, 1986; Garrett, 1975, 1980, 1988; Levelt, 1989; Stemberger, 1985) and production latencies (Roelofs, 1996 a,b; Roelofs, Baayen, & Van den Brink, submitted) suggests that derivational forms are stored in a morphologically decomposed manner. I will discuss the speech-error evidence now and the latency evidence later.

The evidence from speech errors for morphological decomposition concerns failures in the serial ordering of morphemes in an utterance. Some morphemic errors seem to concern the lemma level, whereas others involve the word-form level (e.g. Dell, 1986; Garrett, 1980, 1988). Consider, for example, the morphemic error in "how many PIEs does it take to make an APPLE?" (from Garrett, 1988). The interacting stems belong to the same syntactic category (i.e. noun) and come from distinct phrases, which is also characteristic of whole-word exchanges such as in "we completely forgot to add the LIST to the ROOF" (from Garrett, 1980). Whole-word exchanges typically involve items of the same syntactic category and ignore phrase boundaries (Garrett, 1975). This suggests that these morpheme errors and whole-word errors occur at the same level of processing. They occur during syntactic encoding when lemmas in a developing syntactic structure trade places. Note that the plurality of *apple* is stranded; that is, it is realised on *pie*. This suggests that the abstract morphosyntactic number parameter is set after the exchange. By contrast, the exchanging morphemes in an error such as "SLICEly THINNed" (from Stemberger, 1982) belong to different syntactic categories (adjective and verb) and come from the same phrase, which is also characteristic of segment exchanges such as in "Rack Pat" for "pack rat" (from Garrett, 1988). Segment errors are typically not affected by lemma information such as syntactic category and occur on words within a single phrase. This suggests that this second type of morpheme error and segment errors occur at the same level of processing, namely the level at which word forms are retrieved and the morphophonological form of the utterance is constructed. The errors occur when morphemes or segments in a developing morphophonological structure trade places.

In the classification of speech errors, a distinction is made between contextual and non-contextual errors. Contextual errors involve a misordering within the intended utterance, whereas for non-contextual errors there does not exist a clear source within the utterance. As concerns derivational forms, morphemes of both prefixed words and compounds are involved in speech errors (all examples of errors below are from Stemberger, 1985). Examples of contextual errors involving prefixes are the anticipation error "we have twenty-five DEdollars deductible . . ." (intended as "we have twenty-five dollars deductible . . ."), the perseveration error "it does not explain how an apparent case of rule EXsertion may arise" (intended as "it does not explain how an apparent case of rule insertion may arise"), and the exchange error "a self-INstruct DE. . ." (intended as "a self-destruct instruction"). These errors involve words of different syntactic classes, which suggests that the errors are due to encoding failures at the word-form level. Examples of non-contextual errors involving prefixes are the substitution error "she's so EXquisitive" (intended as "she's so inquisitive"), the addition error "positively or negatively REmarked as . . ." (intended as "positively or negatively marked as . . ."), and the deletion error "they weren't jeal" (intended as "they weren't conjealing"). Similar errors involving prefixes have also been observed for Dutch. These errors are difficult to explain purely in phonological terms, because phonological errors rarely involve more than a single segment or syllable constituent (e.g. Dell, 1986; Stemberger, 1985). Speech error evidence also suggests that compounds have internal morphological structure in the mental lexicon. Examples of misorderings are "oh, you were just closing the LIDBOXes" (intended as "oh, you were just closing the boxlids") and "did we miss the TURN TRAIL-off?" (intended as "did we miss the trail turn-off?"). Again, due to the large number of segments involved, these errors cannot be explained phonologically.

One objection to the speech error evidence may be that speech errors are rare events. By definition, speech errors reflect unusual circumstances that cannot straightforwardly be taken to represent the norm. It may be possible that speakers normally do not assemble a word's form out of its constituent morphemes, but start to make errors when they occasionally try to do so. Below, in a section on morphological structure, I will review findings from a chronometric paradigm that independently support the conclusion that the lexicon contains morphologically decomposed word forms.

In summary, the distributional characteristics of certain morpheme errors are similar to those of segment errors and differ from those of whole-word errors. This suggests that the lexicon contains morphologically decomposed word forms. Thus, the empirical evidence refutes the idea of solving the cross-morpheme syllabification problem by a single "morpheme" node for a morphologically complex form. Something like the wordshape-network solution is needed for Dell's model.

Cross-word Syllabification

The wordshape-network suggestion for syllabification across morpheme boundaries in Dell's model, however, cannot be a general solution. It breaks down on syllabification across word boundaries. For cross-word syllabification, header nodes for combinations of words rather than for combinations of morphemes would be needed. Cross-word syllabification, however, often concerns combinations of open-class items and closed-class items. Since the combinations involve open-class words, a speaker cannot store header nodes and category sequences for all alliances. Thus, the suggestion above for syllabification across morpheme boundaries cannot be used as a general solution to the problem of syllabification across word boundaries.

Consider, for example, the production of the utterance "leg mijn juweel in de doos" ("put my gem in the box"). To increase the speed and fluency of articulation, a speaker might syllabify the utterance as "... $(\text{jy})_\sigma(\text{we})_\sigma(\text{lɪn})_\sigma$ ..." instead of "... $(\text{jy})_\sigma(\text{wel})_\sigma(\text{ɪn})_\sigma$ ...". The coda /l/ of the second syllable of *juweel* is made the onset of the syllable *lin*. The lexical words *juweel* and *in* are combined into the new phonological word *juwelin*. The creation of a new phonological word is optional in this example, but it is obligatory for clitics. Clitics are function words, such as pronouns, determiners, particles, auxiliary verbs, prepositions and conjunctions, which, unlike words of major lexical categories, are phonologically dependent on a host (e.g. Booij, 1995; Levelt, 1989). For example, the reduced form *'s* [əs] of the Dutch adverb *eens* (*now*) cannot stand alone. In producing "geef me het juweel 's" ("please give me the gem now"), *'s* is adjoined to *juweel*. This yields the new phonological word *juweel 's*, which is syllabified as $(\text{jy})_\sigma(\text{we})_\sigma(\text{ləs})_\sigma$. Syllabification across word boundaries poses a difficulty for models that assign segments to syllable slots on a word-by-word basis (for a discussion, see Levelt, 1992).

To conclude, cross-morpheme and cross-word syllabification point to the need to deal with flexibility of syllable membership. The WEAVER model addresses this issue in a particular way.

WEAVER'S RULE-BASED APPROACH

Like Dell's model, WEAVER assumes that the mental lexicon is a network of nodes and links that is accessed by spreading activation (Meyer, Roelofs, & Schiller, in prep.; Roelofs, 1992a,b, 1993, 1994, in press a,b, submitted a,b; Roelofs & Meyer, in press; Roelofs, Meyer, & Levelt, 1996). The network consists of three strata: a conceptual stratum with lexical-concept nodes and links (e.g. GEM(X), STONE(X), IS-A); a syntactic stratum with lemma nodes (e.g. *juweel*), nodes and links for syntactic properties (e.g. LEXICAL–CATEGORY: noun, GENDER: neuter), and slots and fillers for diacritics (e.g. HAS-NUMBER: sg, pl); and, relevant for the present paper, a word-form stratum with metrical structure, morpheme, segment and syllable program nodes and links. The word-form stratum is connected to a syllabary, which is a store of ready-made motor programs for syllables (Levelt, 1989, 1992; Levelt & Wheeldon, 1994).

Figure 3 illustrates the memory representation of the form of *juweel* in WEAVER. The form network consists of three layers of nodes: morpheme nodes, segment nodes and syllable program nodes. Morpheme nodes stand for roots and affixes. Morpheme nodes are connected to the lemma and its parameters (diacritic feature nodes). The stem <juweel> is connected to the lemma of *juweel* and singular. A morpheme node points to the segments that make up its underlying form and, for some words, to its metrical structure. For the storage of metrical structures, a principle of economy holds. WEAVER assumes that the main accent of Dutch words is on the first syllable containing a full vowel (which holds for about 90% of the word tokens), unless the lexical form representation indicates otherwise (Meyer et al., in prep.). Thus, for polysyllabic words that do not have main stress on the first stressable syllable, the metrical structure is stored as part of the lexical entry, but for monosyllabic words and for all other polysyllabic words, it is not stored but computed. For example, the metrical structure for *juweel* [jy.ˈwel] is stored, but for *tafel* [ˈta.fəl] (*table*) it is not. Metrical structures describe abstract groupings of syllables (σ) into feet (Σ) and feet into phonological words (ω). Importantly, it is not specified which segments make up the syllables, nor is the CV pattern specified. The links between morpheme and segment nodes indicate the serial position of the segments within the morpheme. Possible—as opposed to actual—syllable positions (onset, nucleus, coda) of the segments are specified by the links between segment nodes and syllable program nodes. For example, the links in the network specify that /l/ is the coda of [wel] and the onset of [lɪn]. These links are used in retrieving a motor program for a syllable after the actual syllable positions of the segments have been determined by the syllabification process.

Information is retrieved from the network through spreading of activation. Encoding starts when a morpheme node receives activation from a lemma. Activation then spreads through the network in a forward fashion. Each node sends a proportion of its activation to its direct neighbours. There is also spontaneous decay of activation. No further constraints are imposed on the activation process.

The form encoders follow simple selection rules. The rules are implemented in a parallel distributed manner. Attached to each node in the network, there is a procedure that verifies the label on the link between the node and a target node one level up. Procedures are stored with the relevant data structures. Thus, a representation scheme is proposed that is sometimes referred to as "object-oriented" (cf. Bobrow & Winograd, 1977). A verification procedure is triggered when the node's activation level exceeds a threshold. The procedures may run in parallel. Thus, word forms are not planned by a central agent that overlooks the whole process, but by a number of procedures that work in parallel on small parts of the word form (like several spiders making a single web). Similar production systems have been proposed by Anderson (1983) and Kempen and Hoenkamp (1987).

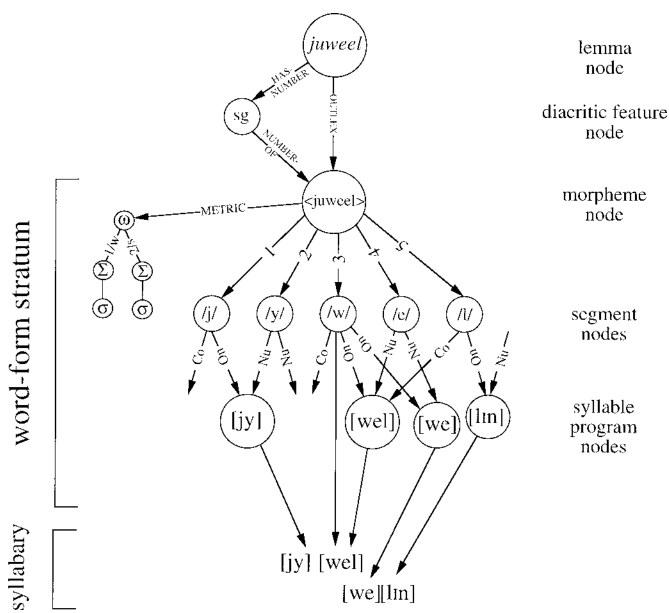

FIG. 3. Memory representation of the word form of *juweel* (*gem*) in WEAVER (Roelofs, 1994, in press a).

The morphological encoder selects the morpheme nodes that are linked to a selected lemma and its parameters. Thus, <juweel> is selected for *juweel* and singular.

The phonological encoder selects the segments and, if available, the metrical structures that are linked to the selected morpheme nodes. Next, the segments are input to a prosodification process that associates the segments to the syllable nodes within the metrical structure (for "exception" words) or constructs metrical structures based on segmental information (see Fig. 4). Thus, when stored, metrical structures are retrieved and woven into the phonetic plan, otherwise they are constructed on the spot. Like weaving a fabric, the process has a certain direction. The prosodification proceeds from the segment whose link is labelled first to the one labelled second, and so forth. In the prosodification process, syllable positions (onset, nucleus, coda) are assigned to the segments following the syllabification rules of the language. Essentially, each vowel and diphthong is assigned to a different syllable node and consonants are treated as onsets unless phonotactically illegal onset clusters arise. Syllabification rules refer to features, so the syllabification process may have to consult a segment's featural composition (part of the syllabary)—this is one of the functions of the direct connection in Fig. 3 from segment node /w/ to the phonetic level; the other function is that it provides for the creation of novel syllable programs directly from segments. In the encoding of <juweel>, the /j/ is made syllable onset and the /y/ nucleus of the first syllable; the /w/ onset, the /e/ nucleus and the /l/ coda of the second syllable. When metrical structure is computed, word accent is assigned to the first stressable syllable.

The prosodification process provides for cross-morpheme and cross-word syllabification. In planning polymorphemic words or connected speech, adjacent morphemes or words may be prosodified together. This leads to new phonological words (Booij, 1995; Levelt, 1989, 1992). For example, WEAVER may syllabify <juweel> with <en> (for the plural *juwelen*) or <juweel> with <in> (for the cliticisation *juwelin*). Following the maximal onset principle in syllabification (e.g. Goldsmith, 1990), /l/ will be made onset of the third syllable instead of coda of the second. In this way, WEAVER achieves syllabification across morpheme boundaries and across word boundaries.

WEAVER's planning of polymorphemic words and cliticisations differs from that proposed by Levelt (1992) in an important respect. According to Levelt (1992), cliticisations like *juwelin* are produced by first combining the retrieved metrical frames for *juweel* and *in*, followed by segment-to-frame association. By contrast, WEAVER does not first combine metrical frames, but starts syllabifying *juweel* and includes *in* only later in the prosodification process. The same holds for the stem *juweel* and the plural suffix *-en* in the production of the plural form *juwelen*.

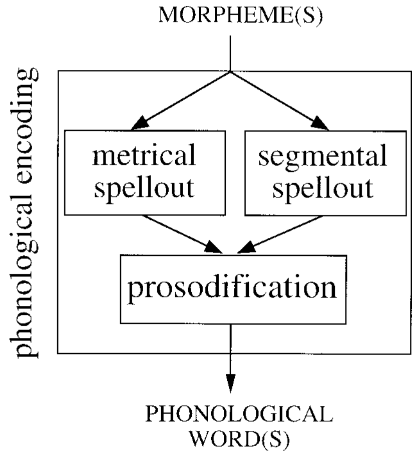

FIG. 4. Phonological encoding in WEAVER: Segmental spellout and, for some words, metrical spellout, followed by a prosodification process that assigns syllable positions to the segments.

The phonetic encoder selects the syllable program nodes whose labelled links to the segments correspond with the syllable positions assigned to the segments. For example, [wel] is selected for the second phonological syllable of *juweel*, because the link between [wel] and /w/ is labelled onset, between [wel] and /e/ nucleus, and between [wel] and /l/ coda. Note that verification prevents a potential selection problem between [wel] and [we] (as there is in Dell's model, as we saw earlier). In planning singular *juweel*, the node [we] will not be selected because there is no coda link between [we] and /l/. Verification also guarantees that the phonetic encoder selects [we] and [lə] for the plural form *juwelen* and [we] and [lɪn] for the cliticised form *juwelin*. Provided that the selection conditions of a syllable program node are met, the actual selection of the node at any moment in time is a random event. The probability of selecting a node at a particular moment in time is equal to the ratio of its level of activation and the sum of the activation levels of all syllable program nodes in the network. Roelofs (1992a,b, 1993, 1996a, in press a) gives the equations that formalise WEAVER. There are expressions for the activation dynamics, the hazard rate (Luce, 1986) of the encoding of a syllable, and the mathematical expectation of the encoding time as a function of these hazard rates.

As a final step, the phonetic encoder addresses the syllable programs in the syllabary, uses the metrical representation to set the parameters for loudness, pitch and duration, and makes the programs available to the articulators for the control of the articulatory movements (Levelt, 1992;

Levelt & Wheeldon, 1994). The syllabary does not have to contain many programs. Statistical analyses by Schiller, Meyer, Baayen and Levelt (1996) revealed that 500 different syllables cover almost 85% of the Dutch syllable tokens. Finally, the hierarchical phonetic plan will govern articulation.

In sum, word-form encoding is achieved by a spreading-activation-based network with labelled links combined with a parallel object-oriented production system. WEAVER also provides for a suspension/resumption mechanism that supports incremental generation of phonetic plans. Incremental production means that encoding processes can be triggered by a fragment of their characteristic input (Levelt, 1989). For example, syllabification can start on the initial segments of a word without having all its segments. Only initial segments and, for some words, the metrical structure are needed. When given partial information, computations are completed as far as possible, after which they are put on hold. When given further information, the encoding processes continue from where they stopped.

THE IMPLICIT-PRIMING PARADIGM

Although WEAVER has been designed to handle, among other issues, problems such as the flexibility of syllable membership, the scope of the model is much wider. For example, I have shown elsewhere (Roelofs, 1994, in press a, submitted a) by computer simulation that WEAVER accounts for key empirical findings about the time course of phonological facilitation and inhibition from spoken distractor words in picture naming (Meyer & Schriefers, 1991), for effects from the order of encoding inside and between the syllables of a word (Meyer, 1990, 1991), for frequency effects (Jescheniak & Levelt, 1994; Levelt & Wheeldon, 1994; Roelofs, 1996b) and for speech error effects (Nooteboom, 1969). Furthermore, new predictions of the model have been validated in recent extensive series of experiments (e.g. Ferrand, Segui, & Grainger, 1996; Hendriks & McQueen, 1996; Meyer et al., in prep.; Pederson & Roelofs, 1995; Roelofs, 1996a,b, in press a,b, submitted a,b; Roelofs, Baayen, & Van den Brink submitted; Roelofs & Meyer, submitted).

A number of key findings about phonological encoding have been obtained with the so-called implicit-priming paradigm developed by Meyer (1990, 1991). This paradigm involves producing words from learned paired-associates. In Meyer's experiments, participants first learned small sets of prompt–response word pairs such as {*steen–juweel*, *wet–jurist*, etc.} ({*stone–gem*, *law–jurist*, etc.}). After learning a set, on each trial one of the prompts (the first word of a pair) was at random visually presented on a computer screen. The task for a participant was to produce the second word of a pair (e.g. *juweel*) upon the visual presentation of the first word (*steen*).

The instruction was to respond as quickly as possible without making mistakes. The production latency (i.e. the interval between prompt onset and speech onset) was the main dependent variable. An experiment comprised homogeneous and heterogeneous response sets. In a homogeneous set, the response words shared part of their form and in a heterogeneous set they did not. For example, the responses shared the first syllable (*JUweel*, *JUrist*, etc.) or the second syllable (*juWEEL*, *houWEEL* (*pick-axe*), etc.) or they were unrelated (*jurist*, *houweel*, etc.). Heterogeneous sets in the experiments were created by regrouping the pairs from the homogeneous sets. Therefore, each word pair was tested both under the homogeneous and the heterogeneous condition, and all uncontrolled item effects were kept constant across these conditions. Meyer found a facilitatory effect from homogeneity only when the overlap was from the beginning of the response words onwards. Thus, a facilitatory effect was obtained for the set that included *JUweel* and *JUrist*, but not for the set that included *juWEEL* and *houWEEL*. Furthermore, facilitation increased with the number of shared segments.

According to WEAVER, this seriality phenomenon reflects the suspension–resumption mechanism that underlies the incremental prosodification of an utterance. Assume the response set consists of *juweel*, *jurist* and so on (i.e. the first syllable is shared). Before the beginning of a trial, the morphological encoder can do nothing, the phonological encoder can construct the first phonological syllable $(\text{jy})_{\sigma}$, and the phonetic encoder can recover the first phonetic syllable [jy]. When the prompt *steen* is given, the morphological encoder will retrieve <juweel>. Segmental spellout makes available the segments of this morpheme, which includes the segments of the second syllable. The phonological and phonetic encoders can start working on the second syllable. In the heterogeneous condition (*jurist*, *houweel*, etc.), nothing can be prepared. There will be no morphological encoding, no phonological encoding and no phonetic encoding. In the end-homogeneous condition (*juweel*, *houweel*, etc.), nothing can be done either. Although the segments of the second syllable are known, the phonological word cannot be computed because the remaining segments are to the left of the suspension point. In WEAVER, this means that the syllabification process has to go to the initial segments of the word, which amounts to restarting the whole process (like unravelling a woven fabric). Thus, a facilitatory effect will be obtained for the homogeneous condition relative to the heterogeneous condition for the begin condition only.

Computer simulations of the experiments of Meyer (1990) can be found in Roelofs (1994, in press a). Advance knowledge about a syllable was simulated by completing the phonological and phonetic encoding of the syllable before the beginning of a trial. For the begin condition, the model yielded a facilitatory effect of −43 msec (real: −49 msec, collapsed across trochaic feet and iambs), whereas for the end condition, it predicted an effect of 0 msec (real: +5 msec). Thus, WEAVER captures the empirical phenomenon.

A similar suspension–resumption mechanism might work for Dell's (1988) model. The speech production system might work its way through the sequence of segment categories corresponding to the *n* shared segments (see Fig. 2). After the *n*th category node has been reached and the corresponding segment has been selected, the encoding process is suspended. The process is resumed when segment $n + 1$ has been made available by the morpheme that is derived from the prompt.

EVIDENCE FOR WEAVER'S SYLLABIFICATION

I now review the outcomes of two series of implicit-priming experiments that specifically support WEAVER's view on syllabification. For details of the experiments, I refer to Meyer et al. (in prep.), Roelofs (1996a,b) and Roelofs and Meyer (in press, in prep.).

Morphological Structure

WEAVER's syllabification algorithm requires morphologically decomposed form entries. The reason for this is that in languages such as Dutch, morphemes such as prefixes, particles, the base verbs of particle verbs and prefixed verbs, and some suffixes constitute independent domains of syllabification (Booij, 1983, 1995). In Dutch, this holds for prefixes such as *ver-* and *ont-*, particles such as *op*, *af*, *aan*, *uit* and so forth, and suffixes such as *-achtig*, but not for suffixes such as *-in*, *-er* and *-ing*. For example, the segment /r/ of the prefix *ver-* of the Dutch verb *vereren* (*honour*) is not syllabified with the base verb *eren*, as the maximal onset principle in syllabification would predict, but is syllabified as the coda of *ver-*. This does not hold for a pseudo-prefixed verb such as *verifiëren* (*verify*), where the /r/ is the onset of the second syllable *ri* instead of the coda of *ver-*. Similar to the prefixed verb *vereren*, the /t/ of the particle verb *uitademen* (*breathe out*) is syllabified with the particle *uit* (*out*) and not with the base verb *ademen* (*breathe*). Also, the final segment /r/ of the base *kinder* (*child*) in *kinderachtig* (*childish*) is syllabified with the base and not with the suffix *-achtig* (contrary to the English translation equivalent). By contrast, the final segment /w/ of *leeuw* (*lion*) in *leeuwin* (*lioness*) is syllabified with the suffix *-in* (*-ess*).

The component morphemes of Dutch compounds also constitute independent domains of syllabification. For example, the Dutch nominal compound *handappel* (*eating-apple*) consists of the morphemes <hand>

and <appel>. The segment /d/ of *hand* in *handappel* is not syllabified with *appel* as the principle of maximization of onset would predict, but is syllabified as the coda of *hand*. Thus, *handappel* is syllabified as (hɑnd)$_\sigma$ (ɑp)$_\sigma$(pəl)$_\sigma$. This does not hold for synchronically pseudo-complex words such as *aardappel* ("*earth apple*", *potato*), which is syllabified as (ar)$_\sigma$(dɑp)$_\sigma$ (pəl)$_\sigma$. In WEAVER, *aardappel* is represented by one node <aardappel> at the morphological level, whereas *handappel* is represented by two nodes, one for <hand> and one for <appel>. Thus, in morphological encoding, the lemma node of the word *aardappel* is mapped onto one morpheme node, just like the lemma node of a simple word like *juweel* (*gem*) is, whereas the lemma node of the compound *handappel* is mapped onto two morpheme nodes. In the next processing step, phonological procedures select the segments linked to these morpheme nodes and syllabify the segments taking each morpheme as a domain of syllabification.

Recent implicit-priming experiments in Dutch have tested for effects of morpheme preparation predicted by WEAVER (Roelofs, 1996a,b; Roelofs, Baayen, & Van den Brink, submitted). For monomorphemic words such as *bijbel* (*bible*) consisting of the morpheme <bijbel>, sharing the first syllable *bij* allows phonological preparation only. In contrast, for polymorphemic words such as *bijrol* (*supporting role*) consisting of the morphemes <bij> and <rol>, additional morphological preparation is possible. In a homogeneous condition where the responses share the syllable *bij*, (bɛi)$_\sigma$ and [bɛi] will have been planned for the monomorphemic word *bijbel* before the beginning of a trial. The morpheme <bijbel> and the second syllable *bel* will be planned during the trial itself. In a heterogeneous condition where the responses do not share part of their form, the whole monomorphemic word has to be planned during the trial. If the first morpheme <bij>, and (bɛi)$_\sigma$ and [bɛi] have been planned for the polymorphemic word *bijrol* before the beginning of a trial in the homogeneous condition, the second morpheme <rol> can be selected during the trial itself, and the second syllable *rol* can be computed. In the heterogeneous condition, however, the initial morpheme <bij> has to be selected first, before segments can be selected for the second morpheme <rol> so that the second syllable *rol* can be computed. Thus, in the case of a polymorphemic word such as *bijrol*, additional morphological preparation is possible before the beginning of a trial. Consequently, extra facilitation should be obtained. Thus, the facilitatory effect for *bij* in *bijrol* (consisting of the morphemes <bij> and <rol>) should be larger than the effect for *bij* in *bijbel* (<bijbel>).

The outcomes confirmed the predictions of WEAVER. In producing disyllabic simple and compound nouns, a larger facilitatory effect was obtained when a shared initial syllable constituted a morpheme than when it did not. For example, the effect was larger for *bij* in *bijrol* (<bij> and <rol>) than for *bij* in *bijbel* (<bijbel>).

In the simulation of the experiment, the homogeneous response sets consisted of *bijrol* (<bij><rol>, *supporting role*), *bijnier* (<bij><nier>, *kidney*) and so forth (the real condition) versus *bijbel* (<bijbel>, *bible*), *bijster* (<bijster>, *loss*) and so forth (the pseudo condition). The heterogeneous sets were created by recombining the responses of different homogeneous sets. The critical items were embedded in a network of 50 randomly selected words (no embedding produced the same simulation outcomes). Advance knowledge about the form of the response word was simulated by completing the morphological, phonological and phonetic encoding of the word form as far as possible before the beginning of a trial. The parameters for WEAVER that fit these data were identical with fits of WEAVER to other data.

Figure 5 presents the results of the simulations. Sharing *bij* in *bijrol* and *bijbel* yields a facilitatory effect. The facilitatory effect for *bij* in *bijrol* (consisting of the morphemes <bij> and <rol>, the real condition) is larger than the facilitatory effect for *bij* in *bijbel* (<bijbel>, the pseudo condition). This corresponds to the empirical findings. To conclude, WEAVER accounts for the empirical phenomenon.

In addition, WEAVER predicts an effect of morpheme frequency for the constituents of polymorphemic lexical items. Frequency effects in the model originate from differences in the speed of running procedures. Speed depends on frequency of usage (more experienced spiders work faster in making a web). This has been tested by Roelofs (1996b, in press b) using the implicit-priming paradigm. High-frequency morphemes are retrieved faster from memory than morphemes of low frequency, so the benefit from preparation should be larger for low-frequency morphemes than for high-frequency ones. This prediction was empirically confirmed. For example, in producing compounds (Roelofs, 1996b), the facilitatory effect was larger for response sets sharing a low-frequency morpheme like <bloem> (*flower*), as in *bloemkool* (*cauliflower*), than for response sets sharing a high-frequency morpheme like <bloed> (*blood*), as in *bloedspoor* (*trace of blood*). Also, in producing particle verbs (Roelofs, in press b), the facilitatory effect was larger for a morpheme like *veeg* (low frequency) in "veeg op!" ("clean up!") than for a morpheme like *geef* (high frequency) in "geef op!" ("give up!").

The results concerning the pseudo and real morphemes and the effect of morpheme frequency show that the implicit-priming paradigm is sensitive to morphological structure. In a compound such as *handappel*, morpheme structure is needed to arrive at the correct syllabification. For compounds whose first morpheme ends in a vowel like *bijrol*, however, morpheme structure is not needed for reasons of syllabification (the correct syllabification would be produced even without access to the word's morpheme structure) but for other formal behaviour such as gapping in a

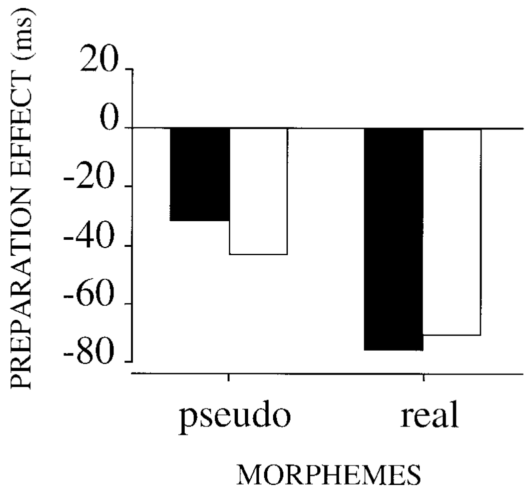

FIG. 5. Mean difference in milliseconds between the production latencies in the homogeneous and the heterogeneous conditions for pseudo and real morphemes. Empirical data (Roelofs, 1996a) and data simulated by WEAVER. ■, Empirical; □, WEAVER.

conjunction (e.g. Booij, 1995). The non-initial morpheme of a compound can be omitted under identity with the non-initial morpheme of an adjacent compound, as in "bij- en hoofdrol" ("supporting and leading role"). This only holds when the morphemes involved are independent phonological words. Prefixes define domains of syllabification but they are not phonological words (Booij, 1995). To test the idea that morpheme structure is stored when it is required for syllabification, Roelofs, Baayen and Van den Brink (submitted) compared the preparation effect for prefixed verbs that need morpheme structure for correct syllabification (e.g. *vereren* (*honour*)) with the preparation effect for prefixed verbs that do not need morpheme structure for correct syllabification (e.g. *verkopen* (*sell*), where /rk/ is an illegal onset cluster in Dutch). In homogeneous sets the responses shared the prefix syllable (e.g. *ver*-), whereas in heterogeneous sets there was no overlap. As predicted, the effect of morpheme preparation was only obtained when morpheme structure was needed for syllabification. Thus, the morphemic effect was only observed for words like *vereren* but not for words like *verkopen*.

To conclude, WEAVER's syllabification algorithm requires morphologically decomposed form entries, because morphemes define domains of syllabification. Larger preparation effects for real than for pseudo morphemes and effects of morpheme frequency show that implicit priming is sensitive to morphological structure. In producing prefixed verbs, effects of morpheme preparation were only obtained for words that require morpheme structure for a correct syllabification.

Metrical Structure

The experiments on morphological structure concern the input to phonological encoding. Other experiments tested WEAVER's claim that phonological encoding involves a parallel spellout of metrical structure and segments, followed by segment-to-frame association (see Fig. 4). WEAVER assigns a specific role to metrical structures in syllabification. For words like the trochee *tafel*, metrical structures are computed on-line, but for words like the iamb *juweel*, metrical structures are stored. The stored metrical structures specify the number of syllables and the stress pattern, but not the precise CV structure of the syllables as the CV headers of Dell (1988) do. The prosodification process in WEAVER associates segments with the syllable nodes within the metrical structure for "exception" words (e.g. *juweel*) or constructs syllable and metrical structures based on segmental information (e.g. for *tafel*). Roelofs and Meyer (in press, in prep.) and Meyer et al. (in prep.) have conducted a series of implicit-priming experiments designed to test WEAVER's view on metrical structure in syllabification.

On each trial, participants had to produce one Dutch word out of a set of three, or four, as quickly as possible. In homogeneous sets the responses shared a number of word-initial segments, whereas in heterogeneous sets they did not. As we have seen, earlier research has shown that sharing initial segments reduces production latencies (Meyer, 1990, 1991; Roelofs, 1996a,b). The responses shared their metrical structure (the constant sets) or they did not (the variable sets).

A first series of experiments (Roelofs & Meyer, in press) tested predictions of WEAVER about the role of metrical structure in the production of polysyllabic words that do not have main stress on the first stressable syllable such as *juweel*. According to the model, the metrical structures of these words are stored in memory. WEAVER's view of syllabification implies that preparation for word-initial segments should only be possible if such response words have an identical metrical structure. If the responses in a set have different metrical structures, segment-to-frame association cannot take place before the beginning of a trial. This prediction was tested by comparing the effect of segmental overlap for response sets with a constant number of syllables such as {*manier* (*manner*), *matras* (*mattress*), *makreel* (*mackerel*)} (all 2 syllables) with that for sets having a variable number of syllables such as {*majoor* (*major*), *materie* (*matter*), *malaria* (*malaria*)} (respectively, 2, 3 and 4 syllables). In the example, the responses share the first syllable *ma*. Word stress was always on the second syllable. As predicted, facilitation was obtained for the metrically constant sets but not for the variable sets. The same predictions were also tested by comparing the effect of segmental overlap for response sets with a constant stress pattern such as {*marine* (*navy*), *materie* (*matter*), *malaise* (*depression*), *madonna* (*madonna*)} (all responses having stress on the second syllable) with that for sets having a variable stress pattern such as {*marine* (*navy*), *materie* (*matter*), *manuscript* (*manuscript*), *madelief* (*daisy*)} (first two responses having stress on the second syllable and the last two responses having stress on the third syllable). All response words were trisyllabic. Again, as predicted, facilitation was observed for the constant sets but not for the variable sets. In sum, the experiments have yielded counterintuitive results that support WEAVER's approach to metrical structure.

The results of these experiments suggest that constancy in CV structure is not necessary to observe a preparation effect, because in none of the homogeneous sets of the experiments was this structure identical across response words (though one could perhaps argue that the response words in the metrically constant sets were more similar in CV structure than those in metrically variable sets). Results obtained by Meyer (1990, 1991) and Roelofs (1996a,b, in press b) also suggest that implicit priming effects can be obtained for homogeneous sets with variable CV structures. However, although constancy in CV structure does not appear to be necessary for obtaining a facilitatory effect, it is still possible that stronger effects arise for sets with constant than with variable CV structure. This is not predicted by WEAVER, but, as explained earlier, others (e.g. Dell, 1988) have argued for an explicit representation of CV structure. Therefore, we explicitly tested whether the size of the preparation effect was affected by the constancy versus variability of the CV structure of the response words. We compared the effect of segmental overlap for response sets having a constant CV structure such as {*bres* (*breach*), *bril* (*glasses*), *brok* (*piece*), *brug* (*bridge*)} (all CCVC responses) with that for sets having a variable CV structure such as {*brij* (*porridge*), *brief* (*letter*), *bron* (*source*), *brand* (*fire*)} (CCVV, CCVVC, CCVC, CCVCC responses, respectively). In the example, the responses share the onset cluster *br*. Facilitation from segmental overlap was obtained for both the constant and the variable sets. The size of the effect was the same for both types of set.

These results suggest that the exact CV structure is not stored, thereby refuting the CV headers of Dell. With constant CV structure, the system might select a header (i.e. CCVC) and work its way through the sequence of segment categories corresponding to the shared segments. After the last shared category node has been reached and the corresponding segment has been selected, the encoding process is suspended. The process is resumed when the first non-shared segment has been made available by the morpheme that is derived from the prompt. With variable CV structure, however, the system cannot select a header and work its way through the sequence of segment categories corresponding to the shared segments. For example, suspension in a CCVV sequence leads to wrong results if it turns out that a CCVVC word has actually to be produced. Nevertheless, empirically, the same amount of facilitation from segmental overlap was obtained for the constant and the variable sets.

WEAVER explains why preparation for word-initial segments is only possible for response words with an identical number of syllables and stress pattern, and why identical CV is not needed. Figure 6 shows the results of simulations comparing the effect of segmental overlap for response sets with a constant number of syllables such as {*manier*, *matras*, *makreel*} with that for sets having a variable number of syllables such as {*majoor*, *materie*, *malaria*}. Varying the place of stress while keeping the number of syllables fixed gives the same results. The parameters for WEAVER that fit these data were identical with fits of WEAVER to other data. As can be seen, WEAVER accounts for the key empirical finding concerning metrical structure. In contrast, if metrical structures are not involved in advance planning or if metrical structures are computed on-line on the basis of segments for these words, sharing metrical structure should be irrelevant for preparation. Then, preparation (i.e. on-line computing the syllable *ma* before the beginning of a trial and computing the remainder of the word

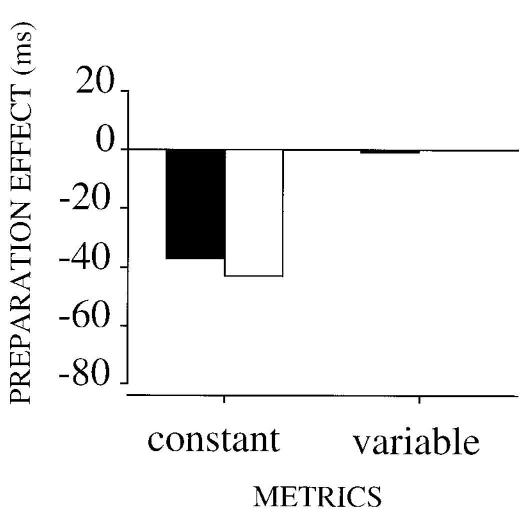

FIG. 6. Mean difference in milliseconds between the production latencies in the homogeneous and the heterogeneous conditions for constant and variable metrics. Empirical data (Roelofs & Meyer, in press) and data simulated by WEAVER. ■, Empirical; □, WEAVER.

form during the trial itself) should be possible for both the metrically constant and variable sets.

Meyer et al. (in prep.) tested predictions of WEAVER about the role of metrical structure in producing monosyllabic words and polysyllabic words whose main stress is on the first stressable syllable like *tafel*. According to the model, the metrical structures of these words are computed on-line by the prosodification process. That is, syllabification and stress assignment is done on the basis of retrieved segments. Consequently, implicit priming of initial segments should now be possible for both metrically constant and variable sets. This prediction was tested by comparing the effect of segmental overlap for response sets with a constant number of syllables such as {*borstel* (*brush*), *botsing* (*crash*), *bochel* (*hump*), *bonje* (*fight*)} (all disyllables stressed on the first syllable) with that for sets having a variable number of syllables such as {*borstel*, *botsing*, *bok* (*goat*), *bom* (*bomb*)} (two disyllables stressed on the first syllable and two monosyllables, respectively). In the example, the responses share the onset and nucleus (*bo*). As predicted, an equal amount of facilitation was obtained for the constant and the variable sets. The same result is predicted for varying the number of syllables of polysyllabic words with an unstressable first syllable (i.e. words with a schwa as the first vowel) and stress on the second syllable. This prediction was tested by comparing the effect of segmental overlap for response sets with a constant number of syllables such as {*gebit* (*teeth*), *gezin* (*family*), *getal* (*number*), *gewei* (*antlers*)} (all disyllables having stress on the second syllable) with that for sets having a variable number of syllables such as {*geraamte* (*skeleton*), *getuige* (*witness*), *gebit*, *gezin*} (two trisyllables stressed on the second syllable and two disyllables stressed on the second syllable, respectively). As predicted, an equal amount of facilitation was obtained for the constant and the variable sets.

Finally, Roelofs and Meyer (in prep.) tested predictions of WEAVER about the production of cliticisations and suffixed forms. According to Levelt (1992), cliticisations like *juweel 's* (e.g. in "geef het juweel 's", "give the gem now") are produced by first combining the retrieved metrical frames for *juweel* and *'s*, followed by segment-to-frame association. By contrast, WEAVER does not first combine metrical frames, but starts syllabifying *juweel* and includes *'s* only later in the prosodification process. The same holds for the stem *juweel* and the plural suffix *-en* in the production of the plural form *juwelen*. These different views were tested by comparing the effect of segmental overlap for response sets that combine disyllabic nouns (e.g. *dozijn* [do.'zɛin] (*dozen*)) with disyllabic verb stems (e.g. *doneer* [do.'ner] (*donate*)) with that of sets combining the disyllabic nouns with trisyllabic cliticised forms of the verbs (*doneer 's*) or with trisyllabic infinitival forms of the verbs (*doneren*). If metrical frames are combined before segment-to-frame association, then the sets with the cliticisations (e.g. the set including disyllabic *dozijn* and trisyllabic *doneer 's*) and the sets with the infinitives (e.g. the set including disyllabic *dozijn* and trisyllabic *doneren*) would be metrically variable, and preparation should not be possible. According to WEAVER, however, all three types of set are metrically constant, since the clitic and the plural suffix are metrically independent elements that are adjoined after the prosodification process has started syllabifying the verb stem. The outcomes of the experiment supported the predictions of WEAVER. The sets with the cliticisations (e.g. the set including *dozijn* and *doneer 's*) and the sets with the infinitives (e.g. the set including *dozijn* and *doneren*) yielded an equal amount of segmental facilitation, and the size of the facilitation was the same as that for the control sets including the disyllabic verb stems (e.g. the set including *dozijn* and *doneer*).

EXPERIMENT

I now report a new experiment testing WEAVER. The experiment had two main objectives. First, it examined whether the facilitatory effect of response homogeneity that Meyer (1990, 1991), Roelofs (1996a) and Roelofs and Meyer (in press) obtained for single words can be generalised to the production of sentential forms. Bock (1987) found that phonological similarity had overall inhibitory influences in a sentence production task. WEAVER predicts facilitation instead of inhibition for implicit priming of sentence production. Secondly, the experiment contrasted Dell's model and WEAVER. In particular, the experiment tested the new suggestion for cross-morpheme syllabification discussed in the Theoretical Positions section. There it is suggested that cross-morpheme syllabification in Dell's model might be achieved by connecting a critical syllable to both morphemes involved and the syllable's segments to category nodes. I argued that this suggestion breaks down on syllabification across word boundaries. Still, it might be a solution for cross-morpheme syllabification. The sentences in the experiment were chosen such that the computation of their sound structure involved encoding across morpheme boundaries. For example, a prompt/response pair in the experiment was *fiets*, "lenen we uit" (literally: *bicycle*, "lend we out"). The morphological and phonological structures of the utterance relate to each other as:

Morphology: $[\,[\text{leen}]_{\text{STEM}}\ [\text{en}]_{\text{AFF}}\,]_{\text{V}}\ [\text{we}]_{\text{PRO}}\ [\text{uit}]_{\text{P}}$
Phonology: $(\,(\text{le})_{\sigma}(\text{nə})_{\sigma}(\text{wə})_{\sigma}\,)_{\omega}\quad ((\Lambda\text{yt})_{\sigma})_{\omega}$

The responses in the experiment are particle verbs such as *uitlenen* (*lend out*), which are combined with a personal pronoun into an elliptical sentence *which leaves out the grammatical object. The object corresponds to the prompt, in the example fiets* (*bicycle*). The pronoun is the reduced form *we* [wə] of the first-person plural nominative form *wij* [wɛi], so the particle verb has to be produced in the plural form. The verb is in the indicative mood. Most importantly, the final segment of the stem morpheme is syllabified with the plural suffix. The final segment /n/ of the morpheme *leen* is syllabified with the plural suffix *-en*, yielding the form $(\text{le})_\sigma(\text{nən})_\sigma$. The plural suffix in Dutch is not an independent domain of syllabification. The stem plus suffix together make up a single phonological word. Furthermore, the reduced form of *wij*, [wə], cannot stand alone, so it is adjoined to *lenen*. The resulting form *lenen we* is syllabified as $(\text{le})_\sigma(\text{nən})_\sigma(\text{wə})_\sigma$. Dutch has a post-lexical rule that deletes the final /n/ of a syllable after a schwa at the end of a morpheme that is not a verbal stem (Booij, 1995). Since this rule applies to the final segment of *lenen*, it is deleted, yielding the form $(\text{le})_\sigma(\text{nə})_\sigma(\text{wə})_\sigma$. Finally, *lenen we* plus the particle *uit* make up the response *lenen we uit.*

WEAVER predicts a facilitatory effect from response-set homogeneity for the production of these sentential forms, similar to that obtained by Meyer (1990, 1991), Roelofs (1996a) and Roelofs and Meyer (in press) for single words. In the homogeneous condition, the encoding process can be suspended after having encoded the first two segments before the beginning of a trial, whereas in the heterogeneous condition such preparation is not possible. In Dell's model, however, advance planning of these sentences in the homogeneous condition is problematic, if not impossible.

The problem posed by these sentences to Dell's model is as follows. Assume that, in the homogeneous condition, the first surface syllable *le* is prepared before the beginning of a trial, and that the remainder of the utterance (*nen we uit*) is encoded during the trial itself. After having prepared the first syllable *le*, supplying a jolt of activation to <leen> (during the trial itself) to retrieve the /onset n/ so as to make it the onset of the next syllable *nen*, the /onset l/ will also be activated. Supplying a jolt of activation to <en> alone is not sufficient, because <en> is connected to all its "allomorphs" *nen*, *len* and so forth—at least, that is the solution we are testing here. Furthermore, the category node C_{On} connects to /onset n/, /onset l/ and so forth. Note further that <leen> is a monosyllabic morpheme, so there will be no changing of spreading rates as would be the case in the encoding of polysyllabic morphemes.

In the heterogeneous condition, the model may account for performance by assuming that the strength of the connection between <leen> and *le* (and thus /onset l/) is stronger than that between <leen> and *nen* (and thus /onset n/). Thus, after having supplied a jolt of activation to <leen>, first the /onset l/ node will be selected. After selection, its activation will be set to zero. Consequently, /onset n/ may be the most highly activated onset node in the encoding of the next syllable, *nen*. However, when preparing the first two segments /onset l/ and /nucleus e/ before the beginning of a trial in the homogeneous condition, supplying (during the trial itself) a jolt of activation to <leen> to retrieve /onset n/ will also activate /onset l/. In fact, given that the strength of the connection between <leen> and *le* (i.e. /onset l/) was assumed to be stronger than that between <leen> and *nen* (i.e. /onset n/), the /onset l/ node will be more active than the /onset n/, and /onset l/ will erroneously be selected. Adding a jolt of activation to <leen> and <en> simultaneously instead of to <leen> only will not help. Recall that <en> is connected to *nen*, *len* and so forth.

In short, preparation of the sound structure of the sentences in the experiment causes an encoding problem in Dell's model. The simplest solution to this problem is to refrain from preparing the response in the homogeneous condition. This would predict that for the sentences in the experiment, no facilitatory effect from homogeneity will be obtained, contrary to the prediction of WEAVER. Consequently, if a facilitatory effect is obtained, this would pose a challenge to the model of Dell (1986, 1988).

Method

Participants. The experiment was conducted with a group of 12 paid participants from the pool of the Max Planck Institute. All participants were native speakers of Dutch.

Materials and Design. The materials were obtained from the Dutch part of the CELEX lexical database (Baayen, Piepenbrock, & van Rijn, 1993). The stimulus materials consisted of two practice sets and six experimental sets of three prompt–response pairs each, listed in Table 1. There were nine different responses, which consisted of elliptical sentences having the same structure as *lenen we uit*. Each set of pairs was tested in a separate block of trials. In three experimental sets (the homogeneous sets) the response words shared the onset and nucleus of the first syllable, and in the remaining three sets (the heterogeneous sets) they were unrelated in form. Thus, in the homogeneous condition, each response was tested together with other responses with the same onset and nucleus of the first syllable, whereas in the heterogeneous condition, the responses tested together in a block did not share part of the first syllable. Following Meyer (1990), the first independent variable—homogeneous *vs* heterogeneous sets—will be called "context". The same prompt–response pairs were tested in the homogeneous and heterogeneous conditions; only their combinations into sets differed. The shared onset and nucleus of the syllables in the homogeneous sets were [zɛ], [le] and [vu]. Each of these syllables was used in one homogeneous set. The second independent variable, which had three levels ([zɛ], [le] and [vu]), will be called "fragment".

Each response was coupled with a prompt that I considered a strong and unambiguous retrieval cue for the corresponding target. All prompts were nouns and all responses were elliptical sentences. The prompt named a typical theme/patient for the verb (e.g. *fiets*, "lenen we uit"; *bicycle*, "lend we out"), so that the association between prompt and response would be a natural one and be easy to remember.

Each participant was tested on all sets. The order of the sets was rotated across participants in the following way. A group of six participants was first tested on the homogeneous sets and then on the heterogeneous sets. For the remaining six participants, the order of testing was reversed. The sets were

TABLE 1
Stimulus Materials

Pairs

gewoonte–leren we af	arrestant–voeren we af	reis–zeggen we af
fiets–lenen we uit	snelweg–voegen we uit	film–zenden we uit
tekst–lezen we op	kind–voeden we op	kraag–zetten we op

Context

Homogeneous		**Heterogeneous**	
Set 1		*Set 1*	
VOEren	we af	zeggen	we af
VOEgen	we uit	lenen	we uit
VOEden	we op	voeden	we op
Set 2		*Set 2*	
LEren	we af	voeren	we af
LEnen	we uit	zenden	we uit
LEzen	we op	lezen	we op
Set 3		*Set 3*	
ZEggen	we af	leren	we af
ZEnden	we uit	voegen	we uit
ZEtten	we op	zetten	we op

Approximate English translation of the verbs:

gewoonte–leren we af	[ˈle.rə.wə ˈɑf]	habit–unlearn
fiets–lenen we uit	[ˈle.nə.wə ˈʌyt]	bicycle–lend out
tekst–lezen we op	[ˈle.zə.wə ˈɔp]	text–read aloud
arrestant–voeren we af	[ˈvu.rə.wə ˈɑf]	prisoner–carry away
snelweg–voegen we uit	[ˈvu.xə.wə ˈʌyt]	highway–take a turn
kind–voeden we op	[ˈvu.də.wə ˈɔp]	child–bring up
reis–zeggen we af	[ˈzɛ.xə.wə ˈɑf]	trip–cancel
film–zenden we uit	[ˈzɛn.də.wə ˈʌyt]	film–broadcast
kraag–zetten we op	[ˈzɛ.tə.wə ˈɔp]	collar–turn up

tested in three successive sections of the experimental session. A different order of the six sets within a section was used for each participant of a group. The three sections will be the third independent variable, which I will refer to as "repetition".

Each of the three prompt–response pairs of a set was tested six times within each block of trials. The order of testing the pairs was random, except that immediate repetitions of pairs were excluded. A different order was used for each block of trials and each participant.

Procedure and Apparatus. The participants were tested individually. They were seated in a quiet room in front of a computer screen (NEC Multisync 30) and a microphone (Sennheisser ME40). After the participant had read the instructions, two practice blocks (a homogeneous and a heterogeneous one with the same structure as an experimental block, but with different items) were administered, followed by the 18 experimental blocks. In the learning phase before each block, the three pairs of a set were presented on the screen. As soon as the participant indicated having studied the pairs sufficiently, the experimenter started the test phase. The structure of a trial was as follows. First, the participant saw a warning signal (an asterisk) for 500 msec. Next, the screen was cleared for 500 msec, followed by the display of the prompt for 1500 msec. The asterisk and prompt were presented in white on a black background. Finally, before the start of the next trial, there was a blank interval of 500 msec. Thus, the total duration of a trial was 3 sec. The experiment was controlled by a Hermac 386 SX computer.

Analyses. After each trial, the experimenter coded the response for errors. Experimental sessions were recorded on audiotape by a Sony DTC55 DAT recorder. The recordings contained the participant's speech and tones indicating the onset of the prompt (1 kHz) and the moment of the triggering of the voice key (2.5 kHz). These tones were also heard by the experimenter (via closed headphones) for each trial. The recordings were consulted after the experiment when the experimenter was in doubt about whether a response was completely correct. Four types of incorrect responses were distinguished. First, a participant might have produced a wrong response. Secondly, the response might have exhibited a disfluency; that is, the participant stuttered, paused within the utterance, or repaired the utterance. Thirdly, the voice key might have been triggered by a non-speech sound (noise in the environment or a smacking sound produced by the lips or tongue). Fourthly, the participant might have failed to respond within a time-out period of 1500 msec. Incorrect responses were excluded from the statistical analysis of the production latencies.

The production latencies and error rates were submitted to by-participant and by-item analyses of variance with context, repetition and fragment as repeated-measures factors.

Results and Discussion

A significant facilitation effect of 28 msec was obtained for context [means for the homogeneous and heterogeneous conditions 680 and 708 msec, respectively, with by-participant standard errors of 5.6 and 5.6 msec, respectively: $F_1(1,10) = 37.29$, MSe $= 3372$, $P < 0.001$; $F_2(1,6) = 11.53$, MSe $= 908$, $P < 0.015$]. Also, main effects of repetition [$F_1(2,20) = 4.03$, MSe $=$ 9814, $P < 0.035$; $F_2(2,12) = 8.79$, MSe $= 398$, $P < 0.005$] and fragment [$F_1(2,20) = 46.13$, MSe $=5254$, $P < 0.001$; $F_2(2,6) = 5.27$, MSe $= 3830$, $P <$ 0.05] were obtained. Context did not interact with repetition [$F_1(2,20) =$ 1.08, MSe $= 5531$, $P > 0.35$; $F_2(2,12) = 2.70$, MSe $= 185$, $P > 0.11$] or fragment [$F_1(2,20) = 6.64$, MSe $= 2631$, $P < 0.006$; $F_2(2,6) = 1.60$, MSe $=$ 908, $P > 0.28$].

In the experiment, the overall error rate (wrong responses and dysfluencies) for the homogeneous and heterogeneous conditions was 1.1 and 1.2%, respectively. The percentage of time-outs was 0.2% for the homogeneous condition and 0.1% for the heterogeneous condition, and the percentage of false triggering of the voice-key was 0.3 and 0.3%, respectively. The statistical analyses of the errors did not yield significant results.

The results support the following two conclusions. First, the experiment shows that the facilitatory effect from response homogeneity that Meyer (1990, 1991), Roelofs (1996a) and Roelofs and Meyer (in press) obtained for single words can also be found for the production of sentential forms. Thus, such a facilitatory effect is also obtained outside naming. Secondly, the facilitatory effect from response homogeneity supports WEAVER rather than the model of Dell. WEAVER predicted the facilitatory effect for the production of these sentential forms. In the homogeneous condition, the encoding process can be suspended after having encoded the first two segments before the beginning of a trial, whereas in the heterogeneous condition, such preparation is not possible. By contrast, it is difficult for Dell's model to explain the advance planning of these sentences in the homogeneous condition.

One objection to the experiment may be that there is no specific evidence that it speaks to syllabification. The small priming effect observed could simply be due to the shared initial consonant only. Although the experiments on metrical structure discussed earlier suggest that the implicit-priming paradigm taps into syllabification, the present experiment may be an exception. Thus, additional controls would be required in subsequent research. Note, however, that even if the advantage for the homogeneous condition would be due to the shared onset segment only, the experiment would still test the proposed new mechanism for cross-morpheme syllabification in Dell's model. Crucial for the test is that response preparation (e.g. *le*) includes selection of the shared initial consonant (i.e. /onset l/), because this would interfere with the selection of the resyllabified onset segment for the second morpheme (i.e. the selection of /onset n/ in producing "lenen we uit").

Another objection to the experiment may be that implicit priming does not tap into morphophonological encoding processes *only* and therefore does not need to reflect the relevant level of encoding in Dell's model. Perhaps Dell may explain the facilitation effect at a phonetic level rather than at a phonological level. However, the problem with this view is, again, that it leaves unexplained the effects from metrical structure discussed earlier. If implicit priming can reflect preparation of segments at a phonetic level only, at least some facilitation should have been obtained in the metrically variable conditions (with the metrically exception words). However, these conditions yielded no facilitation at all. Thus, the facilitation in the current experiment cannot reveal preparation of segments at a phonetic level only but should involve phonological encoding, and therefore poses a challenge to the model of Dell (1986, 1988).

GENERAL DISCUSSION

Models of speech production differ in their claims about syllabification. In a memory-based approach (e.g. Dell, 1986, 1988), the syllable structure of each word is stored in the mental lexicon. In contrast, according to the rule-based approach, the planning of speech involves the assignment of syllable positions to segments after they have been retrieved for a word from memory (e.g. Béland et al., 1990; Levelt, 1992). This paper has made a case for the rule-based approach to syllabification realised in the WEAVER model of speech production (Roelofs, 1994, in press a). I have argued that cross-morpheme and cross-word syllabification pose difficulties for a memory-based approach but not for WEAVER. I have also reviewed empirical support for WEAVER's specific form of syllabification. Finally, I reported a new experiment on syllabification, which supports WEAVER rather than Dell's model.

In this last section, I will discuss an important issue in syllabification that may be investigated (further) in future research, namely the issue of resyllabification in speech production. Is rule-based syllabification achieved in one or two steps?

In Levelt's (1992) view, syllabification occurs only once in the speech production process. In a single syllabification pass, segments receive their ultimate syllable positions in the utterance. For example, the new phonological word $(\text{le})_\sigma(\text{nət})_\sigma$ (*leen 't*, cf. *lend it*, syllabified as $(\text{lɛn})_\sigma(\text{dɪt})_\sigma$) made up of the lexical words *leen* (*lend*) and *het* (*it*) is created by first combining the metrical structures of *leen* and *het* and next associating their segments with this new composed structure (Levelt & Wheeldon, 1994). In contrast, according to the theory of Lexical Phonology, in phonology (Kiparsky, 1982; for reviews, see Goldsmith, 1990; Kenstowicz, 1994; Mohanan, 1986), a clitic would be adjoined to an already syllabified base, followed by resyllabification. For example, $(\text{le})_\sigma(\text{nət})_\sigma$ is created by first fully syllabifying *leen*, adjoining *het*, and resyllabifying the /n/. WEAVER can handle both possibilities, so for the model it is more of an empirical issue than a theoretical one. In the case of syllabification in a single pass, the prosodification of *leen* would already have to take the presence of *het* into account. In contrast, when leen is first fully syllabified, a second step of resyllabification would be needed. Note that on both accounts, syllabification is an active process. Syllable structures of words are not stored in memory, as in models such as that of Dell (1988). I now discuss some evidence for the view of a two-step construction of new phonological words that combine lexical words.

Syllable-final devoicing in Dutch bears on the issue of resyllabification (e.g. Berendsen, 1986; Booij, 1995). For example, the pronunciation of the Dutch word *voed* (*feed*) is [vut]. However, underlyingly the final stem-consonant of the word is voiced (i.e. /d/), which explains the appearance of the /d/ in the plural form [vu.dən]. What happens with this segment when, for example, the word *voed* is combined with the reduced form of the pronoun *hem*, *'m* [əm], in "voed 'm" ("feed him")? With combination of metrical structures prior to association (Levelt, 1992), the underlying /d/ should surface as /d/ (i.e. voiced), but when a clitic is adjoined to an already syllabified base and the /d/ is resyllabified, the underlying /d/ should surface as /t/ (i.e. voiceless). In the case of resyllabification, the /d/ would have occupied a syllable coda position in the derivation, where it would obligatorily undergo the Dutch devoicing rule. Linguistic intuition (Berendsen, 1986; Booij, 1995), acoustic measurements and perceptual judgements by participants (Baumann, 1996) suggest that Dutch speakers say [vu.təm]; that is, the obstruents are voiceless in syllable-onset position. However, native speakers differ in their pronunciations. For some cliticisations, the variants with voiced obstruents are found. This may indicate that syllabification occurs in a single pass for these forms (as proposed by Levelt), or may suggest that certain cliticisations are stored in memory (e.g. high-frequency combinations of hosts and clitics, as proposed by Booij, 1995).

CONCLUSION

In this paper, I have summarised the support for the claim that syllabification is computed by rule as opposed to being directly stored in the mental lexicon (direct storage is claimed by Dell, 1988). First, I argued that models that rigidly store words as sequences of syllable nodes, or models that store each consonant as an onset or coda, have a difficult time dealing with the need for flexibility of syllable membership (i.e. in cross-morpheme and cross-word syllabification). Secondly, I reviewed empirical evidence that supports WEAVER's claim that syllable structure is computed on-line and in a left-to-right fashion. The evidence suggests that syllable structure is computed by associating retrieved segments with the syllable nodes within retrieved metrical structures for polysyllabic words that do not have main stress on the first stressable syllable (which holds for roughly 10% of the Dutch word tokens), and by constructing syllable and metrical structures based on segmental information for monosyllabic words and for all other polysyllabic words (the remaining 90% of the words). Furthermore, I reviewed evidence that supports WEAVER's claim that cross-morpheme and cross-word syllabification is achieved by adjoining a suffix or a clitic to an already partly syllabified base rather than by first combining the metrical frames for the base and for the suffix or clitic followed by segment-to-frame association (contrary to Levelt, 1989, 1992). Whether speech production involves resyllabification is an open issue.

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