On-line versus Off-line Priming of Word-Form Encoding in Spoken Word Production

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Abstract

The production of a disyllabic word is speeded up by advance (off-line) knowledge of the first syllable, but not by knowledge about the second syllable (Meyer, 1990). By contrast, when first-syllable or second-syllable primes are presented during the production of a disyllabic word (on-line), both primes yield a facilitatory effect (Meyer & Schriefers, 1991). In this paper, the computational model of word-form encoding in speaking developed in Roelofs (1992b, submitted) is applied to these contradictory findings. Central to the model is the proposal by Levelt (1992) that morphemic representations are mapped onto stored syllable programs by serially grouping the morphemes' segments into phonological syllables, which are then used to address the programs in a syllabary. Results of computer simulations reported in this paper show that the model resolves the empirical discrepancy.

The production of a disyllabic word is speeded up by advance (off-line) knowledge of the first syllable, but not by such information about the second syllable (Meyer, 1990). By contrast, when first-syllable or second-syllable primes are presented during the production of a disyllabic word (on-line), both first-syllable and second-syllable primes yield a facilitatory effect (Meyer & Schriefers, 1991). The timing of the onset of the facilitatory effects differs.

Meyer (1990, 1991) asked Dutch subjects to learn sets of three or five pairs of words such as *lucht* - *raket*, *berg* - *ravijn*, and so forth (Eng: *sky* - *rocket*, *mountain* - *ravine*, etc.); *lucht* - *raket*, *klerk* - *loket*, and so forth (Eng: *sky* - *rocket*, *clerk* - *ticket-window*, etc.); or *lucht* - *raket*, *rechter* - *bewijs*, and so forth (Eng: *sky* - *rocket*, *judge* - *proof*, etc.). After learning a set, the subjects had to produce the second word of a pair (e.g., *raket* [ra ˈkɛt]) upon the visual presentation of the first word (i.e., *lucht*). The response words shared the first syllable (e.g., *raket* [ra ˈkɛt], *ravijn* [ra ˈvɛin], etc.) or the second syllable (*raket* [ra ˈkɛt], *loket* [lo ˈkɛt], etc.), or they were unrelated (e.g., *raket* [ra ˈkɛt], *bewijs* [bə ˈwɛis], etc). Related and unrelated sets were created by assigning word pairs to other sets. Sharing the first syllable yielded a facilitatory effect, but sharing the second syllable did not. That is, producing each of the words of the set *raket*, *ravijn*, and so forth (first syllable) went faster than producing *raket*, *loket*, and so forth (second syllable), whereas producing each of the words from the latter set went as fast as producing *raket*, *bewijs*, and so forth (unrelated).

Meyer and Schriefers (1991) examined the effect of spoken distractor words on word-form encoding in object naming. Again, the disyllabic targets and distractors shared either the first syllable or the second syllable in common. For example, Dutch subjects had to name a pictured rocket (i.e., they had to say *raket*, [ra ˈkɛt]), where the distractor was *ravijn* ([ra ˈvɛin], first syllable) or *loket* ([lo ˈkɛt], second syllable). Unrelated control conditions for the related ones were created by combining pictures with other distractors in the experiment. The distractors were presented just before (i.e., -300 or -150 ms), simultaneously with, or right after (i.e., +150 ms) the onset of the presentation of the picture. A facilitatory effect was obtained from both first-syllable and second-syllable primes. When the SOAs were between the onset of the critical part of the distractor and picture onset (i.e., between the onset of the speech fragment [ra] of [ra ˈvɛin] and picture onset, and between the onset of the [kɛt] of [lo ˈkɛt] and picture onset), the difference between first- and second-syllable primes was in the timing of the onset of the facilitatory effect. The onset of the effect from first-syllable primes was at an earlier SOA than from second-syllable primes (resp. -150 and 0). With both first- and second-syllable overlap, the facilitatory effect was still present at the SOA of +150.

The experiments of Meyer (1990, 1991) and Meyer and Schriefers (1991) included several other conditions (e.g., involving monosyllables). The findings from these conditions were the same as reported above: Off-line priming is only possible from the beginning of a word onwards, whereas this does not hold for on-line priming. In this paper, I concentrate on the priming of the first versus the second syllable of disyllables, because these are the only conditions that were realized in both the experiments of Meyer (1990, 1991) and those of Meyer and Schriefers (1991). Below, I show how the word-form encoding model of Roelofs (1992b, submitted) accounts for this difference between the off-line and the on-line priming of word-form encoding in spoken word production. First, I review the relevant assumptions of the model. Next, I present the results of computer simulations. The simulations show that the model resolves the empirical discrepancy.

General Background

The model advanced in Roelofs (1992b, submitted) has been proposed to improve upon the existing models of word-form encoding. Most of the existing computational models of word-form encoding in speaking have implicitly been designed to account for the production of isolated words (e.g., Dell, 1986; Dell, Juliano, Govindjee, 1993; Houghton, 1990; Schade & Berg, 1992). Thereby, they have neglected specific demands of word-form encoding in the production of connected speech, as argued extensively in Roelofs (submitted).

First, the encoding in the production of connected speech often does not respect lexical, morphemic, and syllabic boundaries (e.g., Kaisse, 1985; Levelt, 1989, 1992). For example, to enhance the speed and fluency of the articulation of the utterance "there is a yellow rocket in the sky", a speaker might say "there is a yellow (rɔ)$_\sigma$ (kə)$_\sigma$ (tɪn)$_\sigma$ the sky" instead of "there is a yellow (rɔ)$_\sigma$ (kət)$_\sigma$ (ɪn)$_\sigma$ the sky". Here, the coda /t/ of the second syllable of *rocket* is treated as the syllable onset of *in*. That this concerns a change of syllable position instead of "co-articulation" is shown by the flapping of the /t/ (in American English). Phonetically, /t/ becomes [ɾ] instead of [t], which only occurs in syllable onset position. The encoding across lexical, morphemic, and syllabic boundaries provides a challenge to the existing models.

Second, due to the incrementality of connected speech planning, the encoding typically takes place in the context of the activation of aspects of other word forms (e.g., Levelt, 1989). Incremental production asks for an appropriate indexing of the information recovered from memory. For example, if the segments /j/ and /r/ happen to be activated from the morphemes <yellow> and <rocket> simultaneously, the system has to know that the /j/ is retrieved for *yellow* and the /r/ for *rocket*. The existing models solve this binding problem by placing severe temporal restrictions on the spelling out of information (e.g., Dell, 1986). To prevent errors, they assume that the brain prohibits that *yellow* and *rocket* are spelled out simultaneously within a level of processing.

However, a speaker's performance in a picture-word interference experiment demonstrates that word-form encoding remains accurate in the context of the activation of other word forms (e.g., Meyer & Schriefers, 1991). As indicated, in such an experiment, a pictured object has to be named (e.g., a depicted rocket), while at the same time a spoken word presented via head-phones has to be ignored (e.g., the form-related word *robber* or the form-unrelated word *fiddle*). The presentation of a distractor word results in longer object naming latencies compared to the situation without a distractor. The naming latencies increase less with form-related distractors (e.g., *robber*, [ˈrɔ bər]) than with unrelated ones (e.g., *fiddle*, [ˈfɪ dl]), showing that there is a level of processing where speech production and speech perception meet. The number of errors in all three cases (related distractor, unrelated distractor, no distractor) is low. Thus, the system is able to cope with the fact that a distractor makes available inappropriate segments (e.g., /b/) or that it makes available appropriate segments (e.g., /r/) at the wrong moment in time.

The model proposed in Roelofs (1992b, submitted) solves the binding problem by other means than timing. The model provides for an efficient encoding of word forms across lexical, morphemic, and syllabic boundaries. Furthermore, the performance of the proposed encoding algorithm has been shown to remain accurate in the context of the activation of other forms.

Theoretical Assumptions

The theoretical background of this word-form encoding model is the spreading-activation model of lexical access in speaking developed in Roelofs (1992a, 1992b, 1993, in preparation) and the theoretical framework for word-form encoding developed in Levelt (1992). Word-form encoding is conceived of as the second stage of lexical access, the first stage being lemma retrieval (e.g., Dell, 1986; Garrett, 1975; Kempen & Huijbers, 1983; Levelt, 1989, 1992). In lemma retrieval, a representation of the intended lexical concept is used to retrieve the syntactic properties of a word from memory and to provide pointers to its morpho-phonological form. In word-form encoding, the form pointers are used to recover the morpho-phonological properties of the word from memory in order to construct an articulatory program. The brain typically does not construct these programs from scratch. Instead, when available, learned motor programs for syllables are retrieved from a mental syllabary (Levelt, 1989, 1992; Levelt & Wheeldon, in press). A syllabary is a repository of articulatory-phonetic programs for syllables.

Assume a speaker wants to name a rocket. First, the "lemma retriever" takes the lexical concept ROCKET and makes available the syntactic property Noun, a slot for the specification of the word's number, and form pointers. To encode the appropriate word form, singular [ˈrɔ k^{h}ət] instead of plural [ˈrɔ k^{h}əts], the word's number has to be

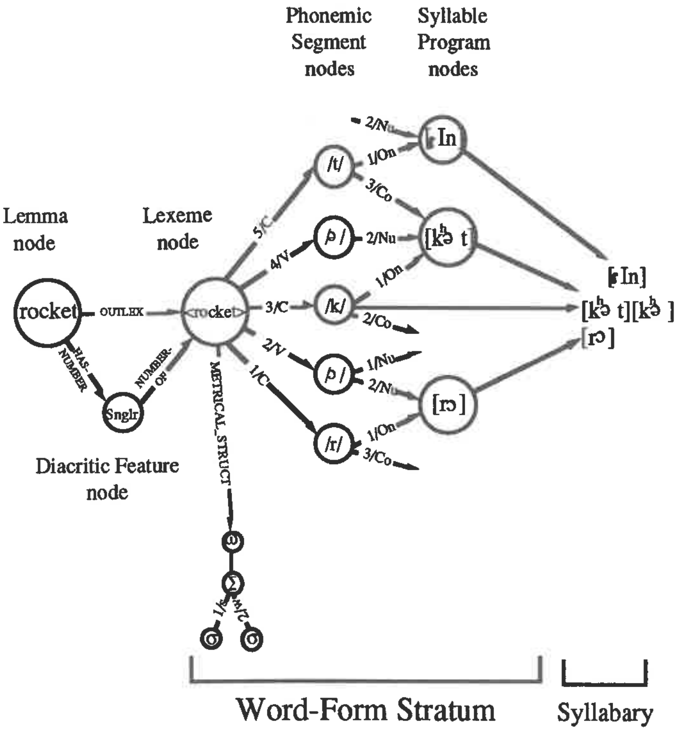

Figure: Memory representation of the word form of *rocket*

specified. The lemma plus the "diacritic" feature singular are input to word-form encoding. The articulatory program is then derived in three major steps: morphological encoding, segmental encoding, and phonetic encoding (Levelt, 1989, 1992). The "morphological encoder" takes the lemma of *rocket* plus the diacritic feature singular, and outputs the morpheme <rocket>. The "segmental encoder" takes <rocket> and produces the phonological word

$$(((\ /\text{r}/_{on}\ /\text{ɔ}/_{nu}\ )_{\sigma s}\ (\ /\text{k}/_{on}\ /\text{ə}/_{nu}\ /\text{t}/_{co}\ )_{\sigma w}\ )_{\Sigma}\ )_{\omega}.$$

That is, it delivers a syllabified sequence of segments, together with a stress pattern over the syllables (cf. Liberman & Prince, 1977). This representation describes *rocket* as a phonological word (ω) consisting of two syllables (σ) making up a foot (Σ). The first, stressed syllable (σ_s) consists of the onset /r/ and the nucleus /ɔ/. The second, unstressed syllable (σ_w) consists of the onset /k/, the nucleus /ə/, and the coda /t/. Finally, the "phonetic encoder" takes this representation and produces the corresponding articulatory program, ['rɔ][kʰət]. This representation describes *rocket* in terms of the syllable programs [rɔ] and [kʰət], the first syllable to be pronounced louder or longer than the second one.

To accomplish an efficient spelling out of lexical information, the theory assumes that the mental lexicon is a network of nodes and labeled links, which is accessed by means of the spreading of activation (cf. Collins & Loftus, 1975). The network consists of three main strata: a conceptual, a syntactic, and a word-form stratum. The conceptual stratum contains lexical-concept nodes and labeled conceptual links, the syntactic stratum contains lemma nodes, slots for diacritics, and syntactic property nodes and labeled links, and the word-form stratum contains morphological and phonological nodes and labeled links (see Figure).

The first layer of the form network consists of lexeme nodes, which are connected to a word's lemma node and its diacritic features. A lexeme node points to a representation of the word-form's metrical structure and to its segmental content (cf. Goldsmith, 1990). The links between lexeme nodes and segment nodes specify the serial position of the segment (i.e., 1/, 2/, etc.) and indicate whether the segment is a consonantal (C) or vocalic (V) constituent (cf. Clements & Keyser, 1983). Segment nodes are connected to syllable program nodes by links that specify the serial position and function (onset, nucleus, or coda) of the segment within the syllable. Finally, each syllable program node points to the actual motor program (e.g., the gestural score, Browman & Goldstein, 1986) for the syllable in the syllabary of the speaker.

Word-form encoding is initiated when a lemma sends activation to the word-form network. Activation then spreads through the network according to

$$a(k, t + \Delta t) = a(k,t)(1 - d) + \sum_n r\, a(n,t),$$

where $a(k,t)$ is the activation level of node k at point in time t, d is a decay rate, and Δt is the duration of a time step. The rightmost term denotes the amount of activation k receives between t and $t + \Delta t$, where $a(n,t)$ is the output of neighbor n, and r indicates the spreading rate. In the incremental planning of connected speech, there may be temporal overlap in the activation of the forms of several words. To select for each of the words the relevant nodes among all the activated ones, the encoders follow simple selection rules. Associated to each node in the form network, there is a routine that tests whether the node has the appropriate relation to the target node(s) at the previous level. Lexeme nodes should appropriately encode the selected lemma and its diacritics, metrical structure nodes and phonemic segment nodes should appropriately encode the selected lexemes, and syllable program nodes should appropriately encode the selected, syllabified segments. A routine is triggered when the node exceeds an activation threshold. The routines can run in parallel.

The morphological encoder selects the lexeme nodes that are linked to the nodes of the selected lemma and its diacritic features. In the example, <rocket> will be selected because it is linked to both the lemma node of *rocket* and the node for singular.

The segmental encoder selects the metrical structure representation and the phonemic segment nodes that are linked to the selected lexeme nodes. The segments are associated from left-to-right to the σ-nodes within the metrical frame (Meyer, 1990, 1991; Levelt, 1992; Wheeldon & Levelt, submitted). Thereby, a syllable structure is assigned following the syllabification rules of the language. New phonological words may be constructed by combining the metrical frames of neighboring words (see Levelt, 1989, 1992). In the example, the string /r/, /ɔ/, /k/, /ə/, /t/, /ɪ/, /n/ is then syllabified as (rɔ)$_\sigma$ (kə)$_\sigma$ (tɪn)$_\sigma$.

As a final step in word-form encoding, for each σ-node the phonetic encoder selects the syllable program node that has the appropriate links to the syllabified segments. For example, the [rɔ] node is selected for (/r/$_{\mathrm{on}}$ /ɔ/$_{\mathrm{nu}}$)$_\sigma$, because the link between /r/ and [rɔ] is labeled as 1/on, and the link between /ɔ/ and [rɔ] is labeled as 2/nu. Finally, the phonetic encoder unpacks the syllable programs, making them available for the control of the movements of the articulators. The selection of a target syllable program node is a random event. The probability of the actual selection of a target node in any moment in time (after its selection conditions have been met) is equal to the ratio of the activation level of the target syllable program node and the sum of the activation levels of all the syllable program nodes in the network. That is,

$$p(\text{ selection } m \text{ at } t < T \leq t + \Delta t \mid \neg \text{ selection } m \text{ at } T \leq t) \\ = a(m,t) \;/\; \Sigma_{\mathrm{i}}\, a(i,t).$$

The index i ranges over the syllable program nodes. The selection ratio equals the hazard rate $h_m(s)$ of the process of the encoding of syllable m (up to the access of the syllabary) at the sth time step. Given the hazard rate functions, the mathematical expectation of the encoding time can be computed (e.g., Roelofs, 1992a, 1992b, 1993, submitted).

Elsewhere, I have shown by means of computer simulations that this model for word-form encoding accounts for key empirical findings about the time course of phonological facilitation and inhibition from spoken distractors in picture naming, about the order of encoding inside and between the syllables of a word, about effects from word and syllable frequency, and about speech errors (see Roelofs, submitted). Furthermore, it has been shown that this model is fully compatible with the model for lemma retrieval proposed by Roelofs (1992a, 1992b). The combination of the two models accounts for classical findings about the time course of semantic and word-form effects from visual and spoken distractors on lexical access in picture naming, picture categorizing, word categorizing, and word naming (see Roelofs, in preparation). Below, I report on simulations showing the model's account for the difference in effect between on-line and off-line priming.

Computer Simulations

The simulations used a network with nodes for the word forms of *raket* (target), *ravijn* (first-syllable overlap), and *loket* (second-syllable overlap), and an unrelated network with an indentical structure. The network approached the structure of the Dutch words used in the experiments of Meyer and Schriefers as close as possible in terms of average number of phonemic segments, CV structure, and so forth. The encoding of the target word-form was simulated following the encoding algorithm described above. In the simulations, a spoken distractor word activated a cohort of compatible elements in the output form lexicon (cf. Marslen-Wilson & Welsh, 1978). For example, for the first λ ms, the speech segment [r] of distractor [ra ˈvεin] activated the phonemic segment node /r/, and somewhat less the lexeme nodes <raket> and <ravijn>; during the next λ ms, the [a] part activated the phonemic segment node /a/, and somewhat less the lexeme nodes <raket> and <ravijn>; during the next λ ms, the [v] part activated the phonemic segment node /v/ and somewhat less the lexeme node <ravijn>, but not the lexeme node <raket> anymore; etc.

The spreading rate r was 0.0120 [ms^{-1}], the decay rate d was 0.0240 [ms^{-1}], and the size of the external input to the network was 0.1965 [ms^{-1}]. In the simulations of the experiment of Meyer and Schriefers (1991), a segment perceived in the spoken distractors provided input to the network for $\lambda = 100$ ms. Lexeme nodes got 10 procent of the external input from the perception of a speech segment. The activation threshold for the triggering of a selection test was 1.5. The latency of a selection test and the syllabification time per syllable equalled $\Delta t = 25$ ms. The correction for the deviation of the mental SOA from the experimental one was +100 ms. The parameter estimates were obtained by fitting the model to the data of Meyer and Schriefers (1991). In the simulations of the experiments of Meyer (1990), advance knowledge about a syllable triggered its segmental and phonetic encoding from left-to-right.

The Table below lists the facilitatory effects as obtained by means of computer simulation of the experiments of Meyer and Schriefers (1991) and Meyer (1990). For the on-line case, the model predicts a facilitatory effect for both the first-syllable and the second-syllable primes. With first-syllable overlap, the model predicts for SOA = -150 ms a facilitatory effect of -28 ms (real: -31 ms). By contrast, with second-syllable overlap, the effect for SOA = -150 ms was -4 ms (real: +10 ms). Thus, the model captures the onset difference. For the off-line case, with first-syllable overlap the model predicts a facilitatory effect of -43 ms (real: -49 ms, collapsed across trochaic and iambic feet), whereas with second-syllable overlap, the effect was 0 ms (real: +5 ms). Thus, the model captures the difference between the patterns of the facilitatory effects from the on-line and the off-line priming of word-form encoding. How does the model explain the empirical findings?

Table: Mean difference between the word production times with related and unrelated syllable primes (in ms). A negative score indicates a facilitatory effect.

On-line priming

SOA	First syllable		Second syllable	
	real	sim	real	sim
-300	-10	-20	11	0
-150	-31	-28	10	-4
0	-43	-61	-38	-17
150	-51	-36	-28	-17

Off-line priming

First syllable		Second syllable	
real	sim	real	sim
-49	-43	5	0

Assume *raket* [ra 'kɛt] is the target. Presenting an unrelated distractor word such as *bewijs* primes the competitor syllable program nodes [bə] and [wɛis]. This increases the denominator of the selection ratios of the syllable program nodes [ra] and [kɛt] relative to the situation without a distractor, which reduces these ratios (and thus the hazard rate of the encoding process), and thus prolongs the process of the encoding of the target. This explains the inhibitory effect from a distractor per se.

Similar to the unrelated *bewijs*, a first-syllable related distractor such as *ravijn* will have an inhibitory component. However, the lexeme <raket> will be in the cohort of *ravijn*, and the segments /r/ and /a/ activate the target syllable program node [ra]. This increases the numerator of the selection ratio of [ra] relative to the non-overlap situation, and thus speeds up the encoding of the target. This explains the facilitatory effect from word-form overlap.

When the second-syllable related *loket* is presented, the target lexeme node <raket> is not activated, because *raket* is not in the cohort of *loket*. Furthermore, initially (i.e., during the first two λ ms) *loket* primes a competitor syllable program node (i.e., [lo]), whereas *ravijn* primed a target (i.e., [ra]). Thus, initially, *loket* acts like an unrelated distractor. Only later on, a target syllable program node will benefit from the form overlap. Although with aligned SOAs the speech segment [k] of *loket* is presented with the same SOA as the [r] of *ravijn*, the facilitatory effect from the [kɛt] of *loket* will be less due to the cohort factor mentioned. This surfaces as a shift of the onset of the facilitatory effect to a later SOA.

Whereas Meyer and Schriefers (1991) obtained a facilitatory effect from second-syllable related distractors on word-form encoding in object naming, Meyer (1990) found no such effect from second-syllable overlap between the words in a response set in experiments without distractors. In the object naming experiments, there was no form overlap between the responses. Thus, whereas in the response-set experiments of Meyer a response preparation could take place (i.e., part of the form of the response word could be planned beforehand), this did not hold for the object naming experiments. According to the model, the absence of a facilitatory effect from second-syllable overlap in the response-set experiments reflects the constraints imposed on a response preparation by the directionality of syllabification. When the syllabification process in word-form encoding operates from the beginning of a word to its end, then response preparation can only occur for a word from its beginning onward. For example, in case of the response set *raket* [ra 'kɛt], *ravijn* [ra 'vɛin] and so forth, the response in each trial can be prepared up to the second syllable, whereas in case of the set *raket* [ra 'kɛt], *loket* [lo 'kɛt] and so forth, such preparation is not possible. In general, off-line priming is only possible for parts of the response word from its beginning onward, as observed by Meyer (1990, 1991). By contrast, in the object naming experiments, the facilitatory effects are not from response preparation (the responses did not share part of their word form in common), but from the priming of retrieval processes, as I discussed above.

Acknowledgements

The research reported in this paper was supported by a TALENT grant from the Netherlands Organization for Scientific Research (NWO). Most of the work was done while I was a Post-doctoral Fellow at the Department of Brain and Cognitive Sciences of the Massachusetts Institute of Technology, Cambridge, MA, USA.

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