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Invited Review

Modeling of phonological encoding in spoken word production: From Germanic languages to Mandarin Chinese and Japanese

ARDI ROELOFS[1]* *Radboud University Nijmegen*

Abstract: It is widely assumed that spoken word production in Germanic languages like Dutch and English involves a parallel activation of phonemic segments and metrical frames in memory, followed by a serial association of segments to the frame, as implemented in the WEAVER++ model (Levelt, Roelofs, & Meyer, 1999). However, for Oriental languages like Mandarin Chinese and Japanese, researchers have suggested that the serial association concerns atonal phonological syllables (Mandarin Chinese) or moras (Japanese) to tonal frames. Here, the utility of these theoretical suggestions is demonstrated by computer simulations of key empirical findings using versions of WEAVER++ for English, Mandarin Chinese (纺 织 者++), and Japanese (ウィーバー++). The simulation outcomes suggest that, although languages may differ in the phonological structure of their words, the principles underlying phonological encoding are similar across languages.

Key words: computational modeling, implicit priming, Japanese, Mandarin Chinese, phonological encoding.

An immediately noticeable difference among the 6000 or so languages of the world concerns the sound form of their words. Languages clearly differ in the segmental repertoire of vowels and consonants as well as in suprasegmental properties such as stress and tone (Ladefoged, 2001; Ladefoged & Maddieson, 1996). In European languages like Dutch and English, one of the syllables of a polysyllabic word carries primary stress. The stress pattern across syllables may sometimes distinguish one word from another, as in the case of English *ab*stract (noun) and ab*stract* (verb). In contrast, Oriental languages like Mandarin Chinese and Japanese make use of tones, whereby the tone pattern across syllables distinguishes words that would otherwise be homophones (Gussenhoven, 2004; Yip, 2002).

The use of tones to differentiate words, analogously to consonants and vowels, is not a rare phenomenon. It has been estimated that more than half of the languages in the world are tone languages (Yip, 2002). A difference among tone languages concerns the phonological units that carry the tones, which is the syllable in Mandarin Chinese and the mora (i.e., a subsyllabic unit that determines syllable weight) in Japanese (Gussenhoven, 2004; Yip, 2002). Moreover, tone languages differ in the number of tones that they use. Mandarin Chinese has four lexically contrastive tones (high, mid-rising, low-dipping, and high-falling)

*Correspondence concerning this article should be sent to: Ardi Roelofs, Radboud University Nijmegen, Donders Institute for Brain, Cognition and Behaviour, Centre for Cognition, Spinoza Building B.02.34, Montessorilaan 3, 6525 HR Nijmegen, The Netherlands. (E-mail: a.roelofs@donders.ru.nl)

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and one neutral tone, whereby the syllables of polysyllabic words may each carry their own tone (Duanmu, 2007). Japanese has only two tones, with one mora of a word carrying high pitch and the other moras bearing low pitch. In Dutch and English, the stressed syllable of a word is pronounced louder, longer, and with a higher pitch than unstressed syllables (Booij, 1995; Kenstowicz, 1994; Levelt, 1989; Roach, 2009). In Japanese, the accented mora of a word is pronounced with a relatively high tone followed by a drop in pitch, while all moras are spoken with equal length and loudness (Akamatsu, 2000; Labrune, 2012).

Over the past few decades, computationally implemented models have been developed for how speakers encode the phonological forms of words in English (Dell, 1986, 1988) and Dutch (Levelt, Roelofs, & Meyer, 1999; Roelofs, 1997). However, it has remained unclear to what extent the encoding principles underlying these Germanic languages, in which words have stress patterns, apply to languages in which tone may distinguish one word from another (Gussenhoven, 2004; Yip, 2002). During the past few years, experimental paradigms that were used to examine phonological encoding in Germanic languages, such as *implicit priming* (Meyer, 1990, 1991), have also been employed in investigating Mandarin Chinese (Bi, Wei, Janssen, & Han, 2009; Chen, Chen, & Dell, 2002; O'Seaghdha, Chen, & Chen, 2010) and Japanese (Kureta, Fushimi, & Tatsumi, 2006). In implicit priming experiments, participants have to produce spoken words in homogeneous blocks of trials in which a word-form property is held constant among the response words (e.g., the first phonemic segment /b/ of the response words *book*, *bed*, and *bus*) and in blocks in which the property varies (e.g., as with the response words *book*, *cat*, and *leg*). Typically, response time (RT) is smaller in the homogeneous than the heterogeneous blocks, often called the *implicit priming effect*, suggesting the benefit of anticipatory preparation of the shared word-form property (here, the segment /b/) in homogeneous blocks.

Implicit priming experiments on Dutch, English, Mandarin Chinese, and Japanese have used very similar designs, which allows for a direct comparison of the results. This has revealed salient differences in implicit priming effects among the Germanic languages, Mandarin Chinese, and Japanese, suggesting important differences in phonological encoding among these languages. In particular, whereas phonemic segments and stress patterns seem to play a dominant role in the phonological encoding of Dutch and English words, such a role is played by syllables and tones in Mandarin Chinese and by moras and tones in Japanese. This raises the question as to what extent the principles underlying the models of phonological encoding developed for English and Dutch apply to Mandarin Chinese and Japanese. This issue is addressed in the present article.

As a theoretical framework for the discussion, the article uses the WEAVER++ model of spoken word planning (Levelt et al., 1999), which has been more extensively applied to findings from implicit priming than the model of Dell (1986, 1988). WEAVER++ has been developed primarily for Dutch but has also been applied to English. The model assumes that phonological encoding in languages like Dutch and English involves a parallel activation of phonemic segments and metrical frames in memory, followed by prosodification, which concerns serial content-to-frame association (for metrically irregular words, discussed below) and syllabification, as illustrated in Figure 1. These assumptions are supported by evidence from implicit priming experiments, which show that sharing of word-initial fragments, including single phonemic segments, yields implicit priming effects, but that sharing of noninitial fragments does not (Meyer, 1990, 1991). However, studies suggest that for obtaining implicit priming effects in Mandarin Chinese, the word-initial fragment has to be minimally a syllable (Chen et al., 2002; O'Seaghdha et al., 2010), whereas it has to be minimally a mora in Japanese (Kureta et al., 2006). Researchers have suggested that for these languages, the serial association concerns stored atonal phonological syllables (Mandarin Chinese) or stored moras (Japanese) to tonal frames. In the research reported in the present

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article, the utility of these theoretical suggestions was examined through WEAVER++ simulations of the key implicit priming findings on English, Mandarin Chinese, and Japanese.

The article is organized as follows. I start by describing phonological encoding in WEAVER++ in somewhat more detail. Next, I explain the implicit priming paradigm, discuss the key findings obtained for Dutch and English, and indicate how WEAVER++ explains these findings. Then, I describe the key findings on Mandarin Chinese and Japanese, and outline how WEAVER++ may be modified to accommodate these findings, following theoretical suggestions in the literature. In particular, I adopt the *proximate units principle* proposed by O'Seaghdha et al. (2010), which holds that languages differ in the phonological units that are directly connected to lexeme (i.e., whole word form) or morpheme nodes in the form network (i.e., segments and metrical frames for Dutch and English, atonal phonological syllables and tonal frames for Mandarin Chinese, and moras and tonal frames for Japanese). Finally, I report the results of computer simulations using versions of WEAVER++ for English, Mandarin Chinese (纺 织 者++), and Japanese (ウィーバー++), which demonstrate the utility of the theoretical suggestions. The simulation outcomes suggest that, although languages may differ in the phonological structure of their words, the principles underlying phonological encoding are similar across languages, with the proximate units principle accommodating language-specific phonological properties, such as whether or not tone is used to distinguish one word from another.

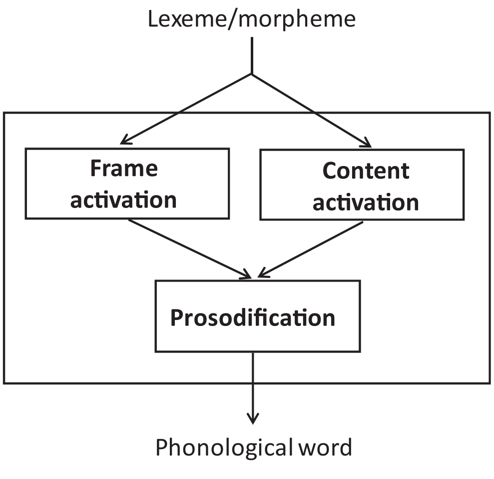

Figure 1 Phonological encoding in WEAVER++ involves parallel activation of phonological contents and frames, followed by prosodification, which includes serial content-to-frame association. Content and frame refer to phonemic segments and irregular metrical structures for Germanic languages like Dutch and English, atonal phonological syllables and tonal structures for Mandarin Chinese, and moras and tonal structures for Japanese.

Phonological encoding in WEAVER++

The WEAVER++ model is described in detail in several other articles and I refer to these publications for a discussion of the model and its empirical support (Levelt et al., 1999; Roelofs, 1997). According to the model, the conceptually driven planning of a spoken word involves conceptual preparation, lemma retrieval, and word-form encoding, with the latter involving morphological, phonological, and phonetic encoding. Information about words is stored in a large associative network that is accessed by spreading activation, while condition-action rules select nodes and perform encoding operations. The network contains nodes for lexical concepts, lemmas, morphemes, phonemic segments, metrical frames (in case the word's stress pattern cannot be derived by rule), and syllable motor programs. For example, for the English word *guitar*, there are nodes for the concept GUITAR(X), the lemma of *guitar* specifying that the word is a noun (for languages such as Dutch, lemmas also specify grammatical gender) and allowing for the abstract morphosyntactic specification of number (singular, plural), the morpheme <guitar>, a metrical frame specifying that stress is on the second syllable, the phonemic segments /g/, /I/, /t/, /ɑ:/, and /r/, and the syllable motor programs [gI] and [tɑ:r]. Activation spreads from level to level, whereby each node sends a proportion of its activation to connected nodes.

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Figure 2 illustrates the representation of the form of *guitar* in the network, including content nodes for the stem morpheme, phonemic segments, and syllable motor programs, as well as frame nodes for the metrical structure. Although previous research has examined the nature of metrical structures in spoken word production (Roelofs & Meyer, 1998), it is still unclear exactly what the metrical frames in memory specify. It has been proposed that these frames make explicit the stress pattern across syllables (Levelt et al., 1999), which may be coded as an abstract grouping of syllables into feet and phonological words (Roelofs, 1996a). However, whether feet are really specified is still unclear. In phonological theory in linguistics, metrical structures are typically represented as metrical trees or grids (Kenstowicz, 1994). The form network illustrated in Figure 2 simplifies earlier proposals by assuming that memory only indicates for each syllable whether it is metrically weak (w) or strong (s), in line with what has been suggested in the literature for tone and tonal frames (Kureta et al., 2006). The issue of what is made explicit by prosodic (i.e., metrical or tonal) frames in memory is taken up in the General Discussion.

In morphological encoding, one or more morphemes are selected for a lemma and its abstract morphosyntactic specification. For example, for the lemma of *guitar* and the specification "singular", the stem morpheme <guitar> is selected. In phonological encoding, condition-action rules select the associated segments (i.e., /g/, /I/, /t/, /ɑ:/, and /r/) and metrical frame (specifying that stress is on the second syllable), and associate the segments to the metrical frame, thereby assigning syllable positions to the segments (e.g., /g/ will become onset of the first syllable). The association proceeds serially from the first to last segment of the word. The online assignment of syllable positions allows for syllabification across morpheme and word boundaries, as in *hea-ring* or *hea-rit* (see Levelt et al., 1999, for extensive discussion). The outcome of phonological encoding is a phonological word representation, which specifies the segments grouped into syllables and the stress pattern across syllables. In phonetic encoding, the phonological word representation is used to retrieve corresponding syllable motor programs (i.e., [gI] and [tɑ:r]) from a mental syllabary, which is a store of ready-made articulatory programs (cf. Cholin, Dell, & Levelt, 2011; Cholin, Levelt, & Schiller, 2006; Levelt & Wheeldon, 1994).

The model assumes short-term buffering facilities for intermediate results (referred to as the "suspend/resume mechanism" in earlier articles, Roelofs, 1997), which is important for the account of implicit priming effects. In normal word planning, these buffers not only support the serial and incremental encoding of morphological, phonological, and phonetic representations, but also will absorb temporal asynchronies that may arise from different speeds of processing at different encoding stages. For example, if a word consists of two

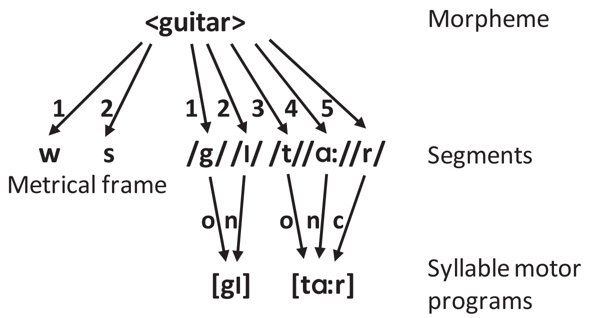

Figure 2 Illustration of the representation of the English word *guitar* in the form network of WEAVER++. c = coda; n = nucleus; o = onset; s = strong; w = weak.

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morphemes, the second morpheme may have been selected while phonological encoding for the first morpheme is still in progress. By temporarily buffering the second morpheme, the temporal asynchrony between morphological and phonological encoding may be resolved. In phonological encoding, syllabification of a word can start as soon as the first few segments are available, as may be the case in the homogeneous condition of implicit priming experiments. The resulting partial representation can be buffered until the missing segments are available and syllabification can continue. Thus, encoding operations are always completed as far as possible, after which they are put on hold. When further information becomes available, the encoding processes continue from where they stopped. Buffered forms in WEAVER++ are only expandable toward the end of the word.

Implicit priming in Dutch and English

The implicit priming paradigm was designed by Meyer (1990, 1991). To overcome the difficulty of finding appropriate pictures to evoke word responses, Meyer used paired-associates. Participants first learned prompt-response pairs, such as CRADLE-*baby*, TOAST-*bagel*, WATER-*basin*. Next, they had to produce the response word of a pair (e.g., *bagel*) upon visual presentation on a computer screen of the prompt word (TOAST). The order of prompts across trials was random. The RT, the interval between prompt onset and speech onset, was the main dependent variable. Response words were produced in two types of trial blocks, homogeneous and heterogeneous. In a homogeneous block, all the response words shared a word-form property, for example, the first syllable (as in *baby*, *bagel*, and *basin*). In the heterogeneous blocks, the response words did not share such form property (e.g., *baby*, *melon*, *hammer*). The response words were tested in both the homogeneous and the heterogeneous blocks of trials.

Using this technique, mean RT is typically shorter in homogeneous than in heterogeneous blocks, the implicit priming effect (Meyer, 1990, 1991). Moreover, a strong effect of serial order is obtained. Sharing of word-initial fragments (e.g., the first phonemic segment, as in *book*, *bed*, and *bus*, or the first syllable, as in *baby*, *bagel*, and *basin*) yields facilitation, but sharing of noninitial fragments does not (e.g., the second syllable, as in *hammer*, *summer*, *beamer*). The magnitude of the implicit priming effect on RTs increases with the number of shared word-initial segments. Moreover, the magnitude of the effect depends on morpheme structure and other abstract linguistic variables (Cholin, Schiller, & Levelt, 2004; Janssen, Roelofs, & Levelt, 2002, 2004; Roelofs, 1997). For example, the implicit priming effect is larger when a shared syllable makes up a morpheme in the response words (e.g., the syllable *in* of *input*) than when the same syllable does not make up a morpheme (e.g., the syllable *in* of *insect*, Roelofs, 1996a; Roelofs & Baayen, 2002), and the effect is larger for low-frequency morphemes compared with high-frequency morphemes (Roelofs, 1996b, 1998). Also, the effect is larger for low-frequency than high-frequency syllables (Cholin & Levelt, 2009). Moreover, there is an implicit priming effect when all words in a block of trials share an initial phonemic segment, but no effect at all when the initial segments share all but one of their phonological features. For example, there is no implicit priming effect for the responses *baby*, *bagel*, and *patient*, where the segments /b/ and /p/ share all phonological features except voicing (i.e., /b/ is voiced and /p/ is voiceless). This suggests that the implicit priming effect of shared phonemic segments arises at the level of phonological rather than phonetic encoding (see Roelofs, 1999, for an extensive discussion). Sharing of only the metrical structure does not yield an implicit priming effect (Roelofs & Meyer, 1998). In line with this, Schiller, Fikkert, and Levelt (2004) also obtained no effect of auditory priming of metrical structure in picture naming.

The implicit priming effect is not only obtained using the prompt-response procedure, but also with picture naming and word reading (Bi et al., 2009; Chen & Chen, 2013; O'Seaghdha et al., 2010; Roelofs, 1999, 2004,

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2006; Santiago, 2000). The latter suggests that the priming effect does not arise from remembering the prompt-response pairs per se, but from the anticipatory preparation and temporary maintenance of partial morphological, phonological, and phonetic codes. Implicit priming effects have been obtained in several European languages, including the Germanic languages Dutch (Meyer, 1990, 1991; Roelofs, 1996a,b, 1998; Roelofs & Baayen, 2002; Roelofs & Meyer, 1998) and English (Damian & Bowers, 2003), and the Romance languages French (Alario, Perre, Castel, & Ziegler, 2007) and Spanish (Santiago, 2000).

Several of the key findings on implicit priming have been simulated by WEAVER++. According to the model, shorter naming RTs in homogeneous than heterogeneous blocks may be obtained when the word production system encodes a partial word-form representation for the response words before the identity of the actual response on a trial is known. This partial representation is temporarily buffered until information about the remainder of the word form becomes available after lexical selection. Consequently, encoding of the buffered representation may be skipped and quicker form encoding may occur in planning the form of the actual response on a trial. For example, if the response words in a block of trials are *book*, *bed*, and *bus*, the first segment /b/ may be selected in advance. Although the actual response on a trial is not predictable (i.e., this may be *book*, *bed*, or *bus*), the /b/ may be prepared regardless of the eventual response. When the overlap is larger (e.g., as in *baby*, *bagel*, and *basin*), more can be prepared (i.e., /b/ and /eI/). Participants are informed about the prompt-response pairs or picture names before the start of a block of trials. Thus, a participant knows in advance what the overlap is among the response words before the first trial of an experimental block and may prepare the response accordingly. In a heterogeneous block of trials (e.g., *book*, *cat*, and *leg*), nothing can be phonologically encoded in advance. Partial preparation is not possible because the response words differ in onset segments (i.e., /b/, /k/, and /l/). Therefore, RTs will be shorter in homogeneous than in heterogeneous blocks, as empirically observed (Damian & Bowers, 2003; Meyer, 1990, 1991). The effects of morphological status (Roelofs, 1996a; Roelofs & Baayen, 2002) and morpheme frequency (Roelofs, 1996b, 1998) suggest that preparation may also happen at the level of morphological encoding. Moreover, the effect of syllable frequency (Cholin & Levelt, 2009) suggests that advance preparation may also involve syllabary access.

Implicit priming in Mandarin Chinese and Japanese

In implicit priming experiments on Mandarin Chinese, Chen et al. (2002) examined the role of syllables and tones. In particular, they tested whether sharing of single onset segments, tones, atonal syllables, and tonal syllables yields implicit priming effects. For example, in the homogeneous condition, the responses shared the first syllable and tone (e.g., *qing1* in *qing1.liang2*, *qing1.sheng1*, *qing1.ting2*, *qing1.jiau1*), the first syllable but not the tone (e.g., *fei* in *fei1.ji1*, *fei2.pang4*, *fei3.cuei4*, *fei4.yan2*), the first segment (e.g., /m/ in *mo1.cai3*, *ma2.que4*, *mu3.dan1*, *mi4.yue4*), or the first tone (e.g., tone 1 in *fei1.ji1*, *ke1.ji4*, *xi1.gua1*, *qing1.jiau1*), whereas the responses did not systematically share part of their form in the heterogeneous condition (e.g., *qing1.liang2*, *xi2.su2*, *fei3.bang4*, *ke4.ben3*). Chen et al. (2002) observed that sharing of the first syllable plus tone yielded an implicit priming effect, which was larger than the effect of sharing the first syllable without the tone. However, sharing the first segment or tone only yielded no effect. The lack of a tone-only effect corresponds to the absence of an implicit priming effect of only sharing metrical structure in Dutch (Roelofs & Meyer, 1998). The results for Mandarin Chinese are illustrated in Figure 3 (black bars). The absence of an implicit priming effect for single initial segments in Mandarin Chinese has been replicated recently by O'Seaghdha et al. (2010) and Chen and Chen (2013). Moreover, O'Seaghdha et al. (2010) observed that sharing of the first segment in English does yield an implicit

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priming effect, in line with earlier findings for Dutch (Meyer, 1990, 1991). These results suggest that phonemic segments and phonological syllables play a different role in Mandarin Chinese than in Germanic languages like English and Dutch (see You, Zhang, & Verdonschot, 2012, for converging evidence from masked priming in Mandarin Chinese). Whereas for getting implicit priming effects in English and Dutch, advance knowledge of the initial segment of a word suffices, the word initial fragment has to be minimally a syllable in Mandarin Chinese to obtain such effects.

There were only 12 participants in each of the experiments of Chen et al. (2002) and O'Seaghdha et al. (2010), which is not a large number. However, the onset priming effect was obtained for English but not for Mandarin Chinese. This suggests that the absence of an effect for Mandarin is not just a matter of lack of experimental power, otherwise the effect should also have been absent for English. Moreover, Chen and Chen (2013) replicated the absence of an onset priming effect for Mandarin Chinese using much larger groups of participants.

In implicit priming experiments on Japanese, Kureta et al. (2006) examined the role of segments and moras. In particular, they tested whether sharing of a single onset segment or first mora yields implicit priming effects. For example, in the homogeneous condition the responses shared the first mora (e.g., *te* in *tezjoo*, *tegami*, *tecuja*) or first segment (e.g., /t/ in *tenshi*, *tonbi*, *tanki*), whereas in the heterogeneous condition the responses did not share part of their form (e.g., *tenshi*, *panda*, *konto*). Kureta et al. (2006) observed that sharing of the first mora yields an implicit priming effect, but that sharing of the first segment does not. These results are illustrated in Figure 4. Thus, whereas for obtaining implicit priming effects in English and Dutch, advance knowledge of the initial segment of a word suffices, the word initial fragment has to be minimally a mora in Japanese to obtain such effects (see Verdonschot et al., 2011, for converging evidence from masked priming in Japanese).

To account for these differences in implicit priming effects among Germanic languages, Mandarin Chinese, and Japanese, O'Seaghdha et al. (2010) proposed the proximate units principle, according to which languages differ in the phonological units that are directly connected to lexeme or morpheme nodes in the form network. The proximal units are phonemic segments and metrical frames for Dutch and English (cf. Levelt et al., 1999), atonal phonological syllables and tonal frames for Mandarin Chinese (cf. Chen et al., 2002), and moras and tonal frames for Japanese (cf. Kureta et al.,

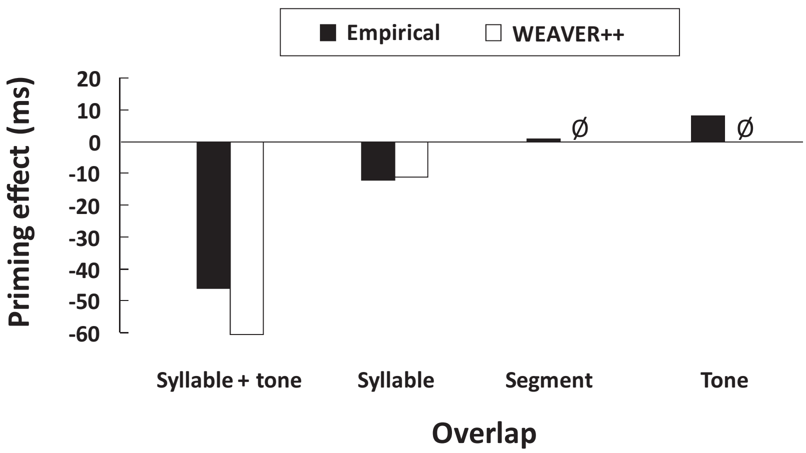

Figure 3 Implicit priming effects as a function of type of overlap in Mandarin Chinese: Real data from Chen et al. (2002) and WEAVER++ simulation results. Ø = No effect in the model.

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2006). Nodes for atonal phonological syllables (Mandarin Chinese) and moras (Japanese) are connected to lexeme or morpheme nodes, on the one hand, and to phonemic segment nodes, on the other hand (cf. Qu, Damian, & Kazanina, 2012). Moreover, content-to-frame association creates phonological word representations that are used to retrieve corresponding syllable motor programs from a mental syllabary (cf. Tamaoka & Makioka, 2009). In the next section, I report the results of computer simulations using versions of WEAVER++ for English, Mandarin Chinese (纺 织 者++), and Japanese (ウィーバー++), which tested the utility of these theoretical suggestions concerning word-form encoding.

Computer simulations for English, Mandarin Chinese, and Japanese

The computational protocol was the same as in previous WEAVER++ simulations of word-form encoding in Dutch (Roelofs, 1996a, 1997, 2002, 2008; Roelofs & Meyer, 1998). The parameter values were fixed and identical to those in earlier simulations. The latency of application of condition-action rules was set to 50 ms. The form network included phonological syllable nodes and four-tone tonal frames for Mandarin Chinese and mora nodes and two-tone tonal frames for Japanese. In all simulations, encoding operations were completed as far as possible given the advance information about form overlap among the response words. Further details are given below.

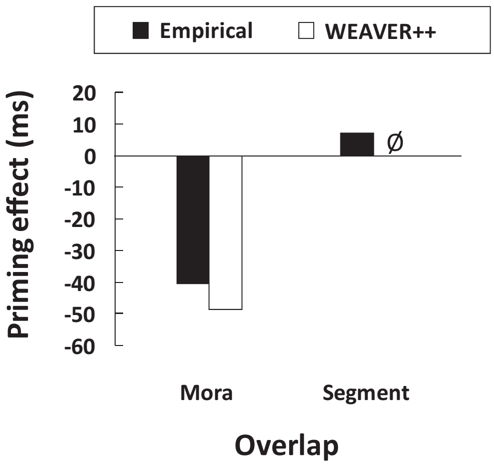

Figure 4 Implicit priming effects as a function of type of overlap in Japanese: Real data from Kureta et al. (2006) and WEAVER++ simulation results. Ø = No effect in the model.

Simulating implicit priming in English

Whereas sharing an onset segment generates an implicit priming effect in Dutch (Meyer, 1991), it yields no effect in Mandarin Chinese (Chen et al., 2002). O'Seaghdha et al. (2010) replicated the absence of an implicit priming effect for shared single onset segments in Mandarin Chinese, and showed that an implicit priming effect for shared onsets is obtained in English, in line with the seminal findings of Meyer (1991) for Dutch. The effect obtained for English was 16 ms using picture naming (O'Seaghdha et al., 2010, Experiment 6).

Computer simulations confirmed that sharing of a single onset segment yields an implicit priming effect for English in WEAVER++. The simulation used a form network as illustrated in Figure 2 for the English word *guitar*. In the homogeneous condition, the responses shared the first segment, like the /g/ in *guitar*, *gazelle*, and *gouache*, whereas there was no such segmental overlap in the heterogeneous condition. Syllabification was assumed to take 25 ms per segment (cf. Indefrey, 2011). Onset overlap yielded an implicit priming effect of 17 ms in the simulations, which corresponds to the empirical results obtained for English (O'Seaghdha et al., 2010).

Simulating implicit priming in Mandarin Chinese

Mandarin Chinese has four lexically contrastive tones and some 400 different atonal syllables, which realize some 1200 different tonal syllables (i.e., 400 possible tonal syllables do not occur). Unlike Dutch and English, there is no resyllabification across morpheme and word boundaries. Moreover, implicit priming experiments suggest that there is no morphological decomposition in production (Chen & Chen, 2007), different from Dutch and English (cf. Dell, 1986; Roelofs,

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1996a,b; Roelofs & Baayen, 2002). Based on their implicit priming results, Chen et al. (2002) and O'Seaghdha et al. (2010) argued that the form network of Mandarin Chinese includes nodes for atonal phonological syllables (linked to phonemic segments) and tones. In the simulations, it was assumed that the form network for Mandarin Chinese contains nodes for lexemes (i.e., whole word forms), tonal frames, atonal phonological syllables (i.e., tonally unspecified), syllabified phonemic segments, and syllable programs specified for tone, as illustrated in Figure 5 for the word *xizang* (Tibet). The high, mid-rising, low-dipping, and high-falling tones are often denoted by the numerals 1, 2, 3, and 4 (and the neutral tone by 0), as is done in Figure 5. In form encoding, atonal phonological syllable nodes and tonal frame nodes are selected for a selected lexeme node, followed by serial syllable-to-tone association. Because segments are already syllabified, segments within an atonal phonological syllable may be selected in parallel. That is, there is no need for serial syllabification as in Germanic languages. The constructed phonological word presentation is used to select the corresponding syllable program nodes.

In the simulations, it was tested whether sharing of a single onset segment, first tone, first atonal syllable, and first tonal syllable yields implicit priming effects, following Chen et al. (2002). Figure 3 illustrates the simulation outcomes, showing that sharing of the first syllable plus tone yielded an implicit priming effect which was larger than the effect of sharing the first syllable without the tone. Moreover, sharing the first segment only or the first tone only yielded no priming effects. These simulation results correspond to the empirical observations of Chen et al. (2002) for a shared tonal syllable (their Experiment 1), atonal syllable (Experiment 2), first segment (Experiment 5), and first tone (Experiment 4).

If the response words in a homogeneous block of trials share the first syllable plus tone, the first atonal syllable and first tone may be selected and associated, the corresponding segment nodes may be selected, and the corresponding syllable program node may be selected in advance. In a heterogeneous block of trials, nothing can be phonologically and phonetically encoded in advance. Therefore, RTs will be shorter in homogeneous than in heterogeneous blocks, as empirically observed. If the response words in a homogeneous block of trials share the first syllable but not the tone, the first atonal syllable and the corresponding segment nodes may be selected, but association

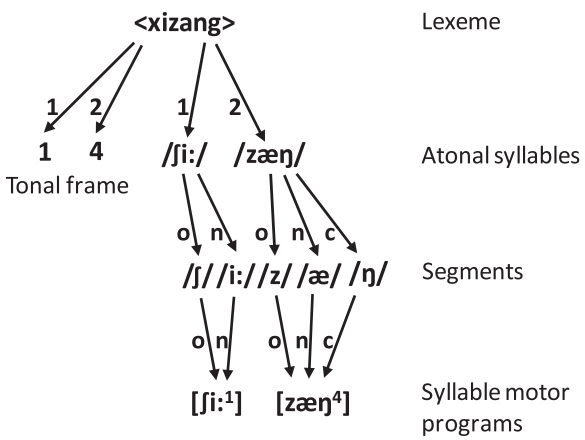

Figure 5 Illustration of the representation of the Mandarin Chinese word *xizang* (西藏) in the form network of WEAVER++. The numbers below the arrows in the tonal frame denote tone numbers. The links between atonal syllables and segments specify syllable positions. Syllable motor programs are specified for tone. 1 = high; 4 = high falling; c = coda; n = nucleus; o = onset.

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to the tone cannot take place. Moreover, a syllable program node cannot be selected, because this depends on the completion of syllable-to-tone association (i.e., syllable programs are specified for tone). Consequently, there will be an implicit priming effect for sharing the first atonal syllable, but this effect will be smaller than when both the first atonal syllable and first tone are shared, as empirically observed. Moreover, when the response words in a homogeneous block of trials share only the first segment, the corresponding segment may be selected. No other node in the network may be selected in advance. Given that the other segments of the first phonological syllable cannot be selected in advance (because they are unknown), the selection of these nodes will set the pace during the planning of the actual response on a trial. As a consequence, no implicit priming effect will occur, as empirically observed. Similarly, when only the first tone is shared, no implicit priming effect will be obtained, as observed.

O'Seaghdha et al. (2010) suggest that participants in implicit priming experiments "intentionally orient" to the proximate units of their language and prepare these if possible. They stated, "Mandarin speakers plan syllables and do not engage onset information even though this would potentially provide a benefit in homogeneous contexts" (p. 290). "Not only do Mandarin speakers use syllable units to plan and regulate speech, but this language property appears to block them from engaging the shared onsets of those syllables" (p. 290). However, the simulation results reveal that this is not a necessary assumption. In the simulations, a shared onset was prepared but this did not yield an implicit priming effect in the RTs. The effect of onset preparation was hidden by the parallel selection of segments of a phonological syllable, made possible by the stored syllabifications (i.e., serial syllabification of segments is assumed not to occur in Mandarin Chinese). Nevertheless, one may argue that the assumption of parallel selection of segments in Mandarin Chinese and serial selection in Germanic languages goes against the generality of the model. If segment selection proceeds serially in Mandarin Chinese, the assumption of no intentional orientation to segments of O'Seaghdha et al. (2010) may account for the absence of onset priming in Chinese. Future studies may further examine these two possibilities (i.e., parallel selection of segments versus no intentional orientation to segments in Mandarin Chinese).

To conclude, the simulations showed that sharing of atonal and tonal syllables yields implicit priming effects in Mandarin Chinese, whereas sharing of single onset segments and first tones yields no effect. In contrast, sharing of single onset segments does yield an implicit priming effect in simulations for English, in agreement with the empirical observations.

Simulating implicit priming in Japanese

Japanese uses two tones, with one mora of a word carrying high pitch and the other moras bearing low pitch. There are some 100 core moras, which together with a number of consonants make up some 300 core syllables in the language (Tamaoka & Makioka, 2009). As in Mandarin Chinese, there is no resyllabification across morpheme and word boundaries. In the simulations, it was assumed that the form network for Japanese contains nodes for lexemes, tonal frames, moras, phonemic segments, and syllable programs, as illustrated in Figure 6 for the word *tenshi* (angel). In form encoding, mora nodes and tonal frame nodes are selected for a selected lexeme node, followed by serial mora-to-tone association and syllabification. The constructed phonological word representation is used to select the corresponding syllable program nodes.

In the simulations, it was tested whether sharing of a single onset segment and first mora yields implicit priming effects, following Kureta et al. (2006). In both cases, the first tone was also shared. Figure 4 illustrates the simulation outcomes, showing that sharing of the first mora yielded an implicit priming effect, but that sharing of the first segment did not. These results correspond to the empirical observations of Kureta et al. (2006) for a shared initial segment (their Experiment 1) and first mora (Experiment 3).

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If the response words in a homogeneous block of trials share the first mora and tone pattern, the first mora and tonal frame nodes may be selected and associated, and the corresponding segment nodes may be selected and syllabified. In a heterogeneous block of trials, nothing can be phonologically encoded in advance. Therefore, RTs will be shorter in homogeneous than in heterogeneous blocks, as empirically observed. If the response words in a homogeneous block of trials share only the first segment and tone pattern, the corresponding segment and tonal frame nodes may be selected. However, given that the first mora cannot be selected in advance (because it is unknown), mora-to-frame association cannot take place in advance but has to be done during the planning of the actual response on a trial. As a consequence, no implicit priming effect will occur, as observed empirically. According to the model, the reason for the absence of an onset effect in Japanese is essentially the same as for Mandarin Chinese. In both cases, onset segments are prepared in the homogeneous condition, but this is not reflected in the RTs because of the dynamics of phonological encoding in these languages.

General discussion

As outlined previously, languages differ in the phonological structure of their words. In line with these differences, studies using the implicit priming paradigm have revealed salient differences in implicit priming effects among Dutch/English, Mandarin Chinese, and Japanese. In particular, whereas sharing of word-initial segments yields implicit priming effects in Dutch and English, the word-initial fragment has to be minimally a syllable in Mandarin Chinese and minimally a mora in Japanese to yield such effects. These results confirm other evidence suggesting that phonemic segments and stress patterns feature prominently in the phonological encoding of Dutch and English words, whereas a dominant role is played by syllables and tones in Mandarin Chinese and by moras and tones in Japanese. The present article addressed the issue of whether the principles underlying the models of phonological encoding developed for English and Dutch apply to Mandarin Chinese and Japanese. According to the WEAVER++ model (Levelt et al., 1999), phonological encoding in Dutch and English involves parallel activation of phonemic segments and metrical frames in memory, which is followed by a serial association of segments to the frame. Researchers have suggested that for Mandarin Chinese and Japanese, the serial association concerns stored atonal phonological syllables (Mandarin Chinese) or stored moras (Japanese) to tonal frames. That is, the proximate units may differ among languages,

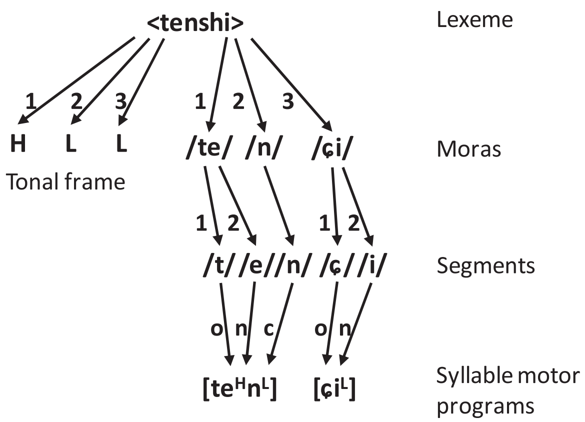

Figure 6 Illustration of the representation of the Japanese word *tenshi* (てんし) in the form network of WEAVER++. Syllable motor programs are specified for tone. c = coda; H = high tone; L = low tone; n = nucleus; o = onset.

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but activation and association processes are similar (cf. O'Seaghdha et al., 2010). The utility of these theoretical suggestions was demonstrated by computer simulations of the key implicit priming findings using versions of WEAVER++ for English, Mandarin Chinese, and Japanese.

The simulation outcomes support the existence of both unity and differentiation of phonological encoding processes among languages. In the remainder of this article, a number of issues are discussed. These issues concern the nature of the metrical and tonal frames, the distinction between stress and tone languages, the status of phonemic segments, subsyllabic effects in Chinese, and the nature of implicit priming effects (i.e., what exactly the implicit priming paradigm measures). I briefly discuss these issues in turn and make suggestions for future research.

Nature of metrical and tonal frames

In the simulations, it was assumed that tonal frames make explicit which of four tones is associated with each syllable of a word in Mandarin Chinese and which mora is associated with the high tone of a word in Japanese, following suggestions in the literature (Kureta et al., 2006; O'Seaghdha et al., 2010). Similarly, it has been assumed that metrical frames make explicit the number of syllables and which of the syllables of a word receives primary stress in Dutch and English (Levelt et al., 1999). The form network needs to specify the stress pattern across syllables only for a minority of the words in these languages (some 10% of all words), because most words have stress on the first stressable syllable. Consequently, for most words in Dutch and English, stress can be assigned by rule. Similarly, a low-high tone pattern is prevalent in Japanese (Kureta et al., 2006), which therefore may be assigned by rule. The Japanese form lexicon needs to specify the tone pattern only for a minority of all words (i.e., some 14%, see Kureta et al., 2006). In contrast, which of the four tones is associated with each syllable of a word in Mandarin Chinese is not predictable and therefore needs to be specified for each word in the form network.

Evidence for the assumption that metrical frames make explicit the number of syllables and which of the syllables of a word receives primary stress in Dutch was obtained in implicit priming experiments by Roelofs and Meyer (1998) using words that did not have stress on the first stressable syllable. The results of the experiments suggested that sharing of the first syllable of these words only yields an implicit priming effect if all response words in a block of trials have the same metrical structure. This suggests that segment-to-frame association can only take place if the full metrical frame is shared. However, subsequent (yet unpublished) experiments by Meyer and the author failed to replicate this finding. Instead, implicit priming effects were obtained regardless of whether the full metrical frame was shared or not. These results suggest that for words with an unpredictable stress pattern, the form network only indicates which of the syllables receives primary stress rather than specifying both the number of syllables and the syllable receiving primary stress. Similarly, for Japanese, given that one mora of a word carries the high tone and the other moras bear the low tone, it may be that the form network only specifies which of the moras carries the high tone rather than indicating for each mora whether it bears the low or high tone, as assumed by Kureta et al. (2006). Future experiments may examine this latter possibility by testing for implicit priming effects using response words that share the first mora plus low tone, but vary in whether the high tone is on the second or third mora.

Distinction between stress and tone languages

In Dutch and English, the stress pattern across syllables may distinguish one word from another, whereas in words in Mandarin Chinese and Japanese, the tones associated with syllables may distinguish words that would otherwise be identical in form (Gussenhoven, 2004; Yip, 2002). Tone is used in standard Dutch and English as part of intonation patterns (Roach, 2009), but it is not lexically distinctive. Moreover, intonational pitch accent is assigned by rule to the syllable carrying primary stress

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within a word. However, some dialects of Dutch, such as Roermond Dutch, do use tone in a lexically distinctive manner (Gussenhoven, 2004), and therefore tone should be specified in the form lexicon of the speakers of those dialects. Moreover, it has been argued that words in Mandarin Chinese have stress patterns, although much less obviously than in Dutch and English (Duanmu, 2007). Words of two or more syllables can show different levels of stress, with unstressed syllables showing vowel reduction or tone neutralization. These cases blur the distinction between stress and tone languages, and suggest that the suprasegmental frames for some dialects of Dutch and for Mandarin Chinese should specify more than, respectively, stress and tone. Future implicit priming experiments may examine this issue by manipulating tone in Roermond Dutch and stress in Mandarin Chinese.

Status of phonemic segments

In the simulations, it was assumed that the proximate units differed among languages (i.e., atonal syllables and four-tone tonal frames for Mandarin Chinese and moras and two-tone tonal frames for Japanese), but that the form network contains phonemic segment nodes linked to a syllabary for all languages. Evidence that the form network of Mandarin Chinese contains segments nodes has been provided by Qu et al. (2012), who obtained segmental effects in naming colored pictures in an electrophysiological (EEG) study. Event-related brain potentials (ERPs) differed between a condition in which picture and color name shared the onset segment and a condition in which they did not. However, there was no RT difference between the conditions. This suggests that segments may play a role in planning the production of words in Mandarin Chinese, without yielding a behavioral effect. Similarly, initial segments were actually prepared in the segment-only condition of the WEAVER++ simulations for Mandarin Chinese, reported in the present article. However, advance preparation yielded no implicit priming effect on latencies in the model because the preparation was hidden by the selection of the other segments of the first syllable during the planning of the actual response on a trial. Future EEG experiments may examine whether segments play a role in planning spoken words in Mandarin Chinese and Japanese by measuring ERPs in segment-only and tone-only conditions.

Subsyllabic effects in Chinese

Using implicit priming in a different dialect of Chinese, namely Cantonese, Wong, Huang, and Chen (2012) observed that sharing the first syllable of disyllabic words yields an implicit priming effect, but that sharing of the first segment does not, thereby replicating previous findings obtained for Mandarin Chinese. However, sharing the body (i.e., onset and nucleus) of the first syllable also yielded an implicit priming effect, although the magnitude of the body effect was smaller than the syllable effect. This priming effect of body overlap may suggest that subsyllabic units play a role in Cantonese phonological encoding (cf. Wong & Chen, 2008, 2009). Alternatively, Verdonschot, Nakayama, Zhang, Tamaoka, and Schiller (2013) suggested that the subsyllabic effect may relate to the fact that participants in the experiments of Wong and colleagues were Cantonese-English bilinguals, who learned English as a second language when they were young. Perhaps there was an influence from English on phonological encoding in Cantonese for these participants. Using masked priming, Verdonschot et al. (2013) observed that under certain experimental conditions a subsyllabic onset priming effect may be obtained in highly proficient Mandarin-English bilingual speakers, suggesting that characteristics of phonological encoding in a second (Germanic) language may exert an influence on phonological encoding in a first (Chinese) language. Future studies may further empirically examine this possibility. Elsewhere, WEAVER++ has been applied to bilingual language production. For an account of bilingual phonological encoding, including computer simulations, I refer to Roelofs (2003) and Roelofs and Verhoef (2006), and for an account of bilingual lexical selection, see Roelofs, Dijkstra, and Gerakaki (2013).

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Nature of implicit priming effects

The implicit priming paradigm has been one of the workhorses in examining the unity and differentiation of phonological encoding among languages. The conclusions from experiments using this paradigm are based on the assumption that implicit priming effects reflect anticipatory preparation of word forms. This was also assumed in the WEAVER++ simulations. However, although this assumption is widely accepted, alternative interpretations are possible. In particular, the homogeneous blocks not only provide prior information about response properties to the participants, but also cause that the relevant attribute is repeated from one response to the next. It therefore remains possible that implicit priming effects are caused by this repetition of response properties rather than by advance preparation, at least for Germanic languages (the absence of onset priming in Mandarin Chinese and Japanese already argues against a mere repetition account for these languages).

These two accounts (preparation vs. repetition) were tested in two experiments in Dutch (Roelofs, 2013). Rather than manipulating advance knowledge between blocks of trials, it was manipulated trial-by-trial by using cues, controlling for repetition of response properties between trials. On each trial, a visual cue indicated two possible responses, one of which had to be produced. The cued responses shared a form property (homogeneous) or they did not (heterogeneous). In one experiment, the form property was the first syllable, and in the other experiment, the properties were the first syllable and first morpheme. The cues varied from trial to trial so that no property repetition occurred across trials. For example, a homogeneous cue indicated that *basin* and *bagel* were the possible picture naming responses on a particular trial. Next, following a short delay, a picture of a basin or a bagel was presented, which had to be named. A heterogeneous cue indicated, for example, that *basin* and *melon* were the possible responses, which was followed by the presentation of a picture of a basin or a melon. The RT was shorter following homogeneous than rather than heterogeneous cues, replicating the standard implicit priming effect that is obtained with homogeneous and heterogeneous blocks of trials (Meyer, 1990, 1991). Cueing syllables plus morphemes yielded a larger priming effect than cueing syllables only, replicating the results of Roelofs (1996a,b) and Roelofs and Baayen (2002). These results suggest that implicit priming effects in Dutch reflect anticipatory preparation of form properties rather than repetition of these properties from trial to trial.

Conclusions

To recapitulate, RT experiments have shown that whereas sharing word-initial segments yields implicit priming effects in Dutch and English, the initial fragment has to be minimally a syllable in Mandarin Chinese and minimally a mora in Japanese to yield such effects. The outcomes of simulations using WEAVER++ versions for English, Mandarin Chinese, and Japanese support the suggestion that by adopting the proximate units principle, the differences in implicit priming effects among languages can be explained. The present results suggest that although languages differ in the phonological structure of their words, the principles underlying phonological encoding are similar across languages. Word forms of different languages seem to be "woven on the same loom".

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