When words come to mind: Electrophysiological insights on the time course of speaking and understanding words

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1. Introduction

Speaking involves the translation of an idea into a linear sequence of sounds. Whereas an idea, or thought, is verbally unspecified, speech consists of strings of words with a clear temporal order. A listener needs to extract the meaning of the sequence of spoken sounds by mapping the acoustic signal onto the appropriate words in the mental lexicon. A few decades of psycholinguistic research has provided detailed information about the different processing levels underlying speaking and listening. An issue that is still under debate, however, concerns the orchestration in real time of the retrieval of the distinct types of knowledge required to produce and understand fluent speech. In recent years electrophysiological methods have provided data that enable a fine-grained temporal analysis of production and comprehension processes. In this chapter, we will review recent studies that have used event-related brain potentials (ERPs) to track the time course of semantic, syntactic and phonological processing stages in the production and comprehension of single words and noun phrases. These studies have provided estimates of the time that is needed for the retrieval of distinct types of lexical information. We will use these time course data to evaluate predictions from computational models of language processing. Specifically, we will compare the empirical data with the time course estimates derived from the WEAVER++ model of speech production (Levelt, Roelofs, and Meyer 1999). Obviously, the data could also be used to evaluate alternative models of speech production (e.g., Caramazza 1997; Dell 1986) and comprehension (e.g., Norris 1994; Perfetti 1999). Although an interesting enterprise, it is beyond the scope of this chapter to critically review all current models of speech production and comprehension in the light of the available ERP data. Instead, we will focus on testing one specific model (WEAVER++) to demonstrate the value of electrophysiological data for language production and comprehension research. Before discussing the ERP studies, we will briefly sketch the main characteristics of WEAVER++, and describe the ERP method that was used to examine temporal parameters of language processing.

2. A model of speech production: WEAVER++

In describing the processing mechanisms underlying the transformation of a thought into speech, theories of speech production usually distinguish between semantic, grammatical, and phonological processing levels (e.g., Bock 1982; Butterworth 1989; Dell 1986; Garrett 1975, 1980; Kempen and Huijbers 1983; Levelt 1989). At the semantic level an input structure is prepared for the speech formulator. This input structure is often called the message (e.g., Garrett 1975; Levelt 1989), and selects from the many aspects of an idea the ones to be uttered. The message represents the speaker's intention, and specifies the content of the utterance. During grammatical processing, the semantic structure is translated into a syntactic representation. The semantic structure drives the activation and selection of the appropriate word representations in the mental lexicon. These representations are often called *lemmas* (Kempen and Huijbers 1983), and can be thought of as entries in the mental lexicon specifying a word's syntactic properties. Lemma activation makes available the syntactic characteristics of a lexical item that are needed for grammatical encoding (such as word-class and grammatical gender; see Kempen and Huijbers 1983; Levelt 1989; Roelofs 1992). Grammatical procedures are initiated to assign syntactic relations between the lexical items, and to determine their serial order in the utterance (Levelt 1989). During phonological processing, the sound form of the utterance is created. This involves the retrieval from the mental lexicon of the phonological properties of the words (e.g., the phonological segments of a word, its stress pattern, and its number of

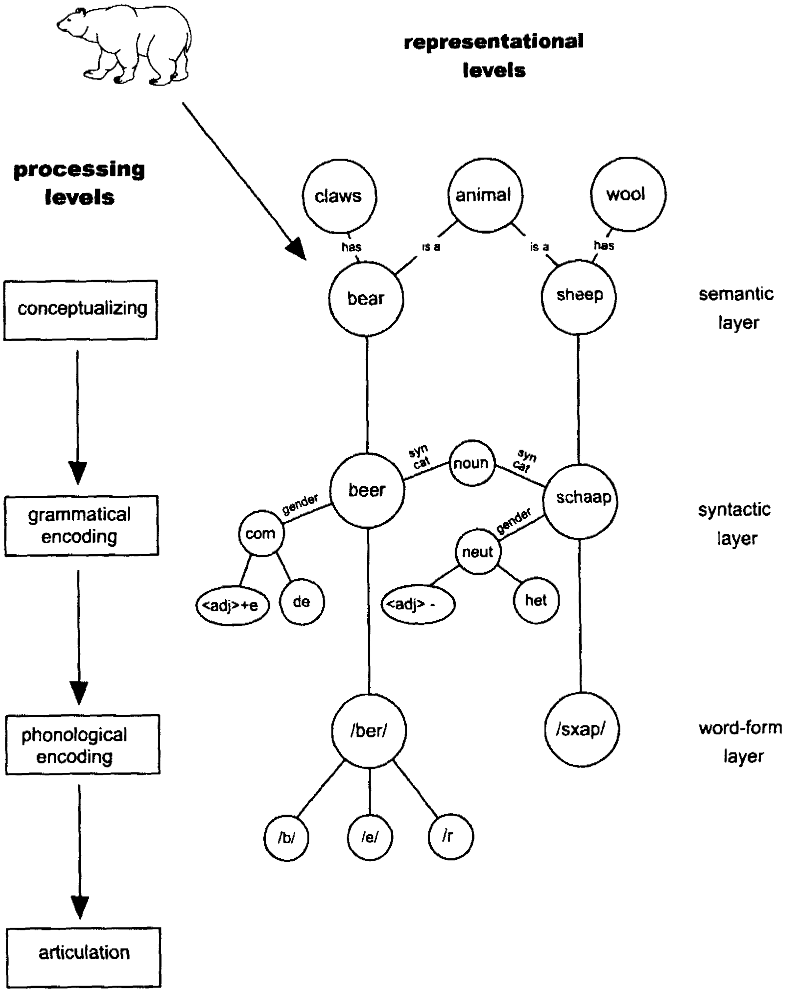


Figure 1. Illustration of the WEAVER++ model of speech production

syllables), and the construction of larger phonological units (e.g., phonological words and phrases). The end product of phonological encoding is a phonetic plan of the utterance to be executed by the articulators (for details see, for example, Dell 1986; Levelt 1989; Meyer 1992).

Figure 1 depicts the structure of WEAVER++. In this model, the mental lexicon is conceived of as a network, and information is retrieved from the network by means of spreading activation. The lexical network consists of three layers of nodes. First, at the semantic layer there are concept nodes and labeled links between the nodes. Following Collins and Loftus (1975), each node represents a single concept, and the meaning of the concepts is stored via labeled links between the nodes. For example, the 'is-a' link between the concept *bear* and the concept *animal* specifies that bear is a subtype of animal. Each lexical concept (that is, a concept for which a word exists) is represented by an independent node. The lexical concept nodes are linked to nodes at the second layer of the network: the syntactic layer. The syntactic layer contains lemma nodes, syntactic property nodes, and labeled links between them. At this stratum, the syntax of words is specified. For example the 'syntactic category' link between the lemma node *bear* and the syntax node *noun* indicates that the word "bear" is a noun. Lemmas also contain morpho-syntactic slots for parameters to be filled in during grammatical encoding, such as tense (e.g., present or past), number (single or plural), and person (first, second or third). The next layer is the word-form layer. In this layer, word-form nodes are linked to lemma nodes and they represent roots and affixes. Word-form nodes point to segment nodes, and to the metrical structure of a word. The actual syllables of a word are constructed on line, and depend on the phonological context in which a word occurs.

3. Temporal characteristics of speech production in WEAVER++

An important characteristic of the WEAVER++ model of lexical access is that it explicitly incorporates time information (Levelt, Roelofs, and Meyer 1999). Lemmas are retrieved by means of forward spreading of activation in the network. As a result of semantic encoding, activation spreads through the conceptual network down to the syntactic stratum. Due to the spreading of activation at the semantic layer a set of lemma nodes will be activated. The activational level of a lemma can be computed for each particular point in time. A lemma's activational level is determined by its activation at point *t*, and the rate with which this activation decays, plus the activational level of the connected nodes and the weights on the links between the nodes. The probability that a lemma indeed becomes selected at a particular point in time is given by the ratio of its own activational level and the activational level of other lemma nodes at that point in time (the Luce ratio). The expected lemma retrieval time can be computed given this ratio (see Roelofs 1992 for details). Once a lemma has been selected, activation spreads to the word-form stratum. The important assumption at this point in the theory is that *only* selected lemmas will activate their word form. For the time course of word retrieval this assumption implies that lemma selection will always *precede* activation of the word form. In the word-form stratum, activation spreads forward from word-form nodes to segment and syllable nodes. Nodes are selected according to similar rules as described for lemma selection. When a word-form node has been activated by its lemma, it immediately activates all of its segments, and its metrical frame. To achieve syllabification, the segments are associated with the syllable nodes within the metrical frame. The association proceeds from left to right: from the segment whose link is labeled first to the one whose link is labeled second and so forth. This implies that a word form is built up in a serial order, from its beginning to its end.

4. Using event-related brain potentials to track the time course of speaking

To examine the temporal dynamics of retrieving distinct types of lexical information at the millisecond-level, an on-line measure is required that taps into these processes as they proceed in time. Although reaction time research has provided insights into the coarse temporal organization of the processes involved in speaking (see, for example, Levelt et al. 1991), reaction times do not provide a continuous measure of the ongoing process. Recently, event-related brain potentials (ERPs) have been introduced into the field of speech production research. One of the attractive characteristics of ERPs is that they provide a continuous measure of the brain's electrical activity as it occurs in real-time. However, because of the artifacts that are evidently caused by the physical realization of speech, the investigation of brain potentials preceding and during speaking has been controversial (but see Eulitz, Hauk, and Cohen 2000 for a study on EEG correlates of phonological encoding during picture naming). In recent studies, however, these problems have been overcome by the use of an experimental paradigm that taps into separate processing stages of speech production before articulation has started. The experimental paradigm involves the measurement of the lateralized readiness potential (LRP), and the N200 component in connection to a task that combines a response decision with a go/nogo judgment.

4.1. The Lateralized Readiness Potential (LRP)

The lateralized readiness potential (LRP) is derived from the readiness potential (RP), a negative-going, motor-related brain potential that starts to develop 800 to 1000 ms prior to the onset of voluntary (hand) movements (Kornhuber and Deecke 1965). Later portions of the RP develop asymmetrically over the left and right motor cortex, being more negative over the scalp site contralateral to the moving hand. Kutas and Donchin (1980) showed that the lateralization of the readiness potentials was directly affected by the extent to which individuals were informed about the response hand. This finding led them to suggest that the asymmetric part of the readiness potential can be used as an index of motor preparation. Consistent with this idea, single cell recordings from monkey cortex showed that the lateralized part of the readiness potential is generated, at least in part, in the motor cortex (e.g., Arezzo and Vaughan 1980; Miller, Riehle, and Requin 1992; Requin 1985; Riehle and Requin 1989). Moreover, scalp recorded ERPs from humans showed that the amount of lateralization of the readiness potential appears to be directly related to the onset of overt motor behavior. That is, an overt response is initiated at the moment at which the lateralized readiness potential has reached a particular threshold value (Gratton et al. 1988). In addition, it has been shown that the readiness potential can start to lateralize even when a response has not yet been completely specified, suggesting that the onset of the LRP is related to motor preparation, and not execution (for an overview see Coles 1989; Coles et al. 1995). Together these findings support the idea that the lateralized part of the RP provides a real-time measure of selective response preparation.

To isolate the lateralized part of the RP from all other lateralized potentials, the LRP is computed with respect to the correct response hand (cf. Coles 1989; De Jong et al. 1988). First, on each trial the amount of lateralized activity is obtained by subtracting the potentials recorded from above the left (C3') and right (C4') motor cortices. These difference waveforms are averaged separately for trials in which the left versus the right hand was cued (Figure 2A). Second, to cancel out lateralized potentials that are not specifically related to response preparation, the average lateralization obtained for the left-hand trials is subtracted from the average lateralization obtained for the right-hand trials (Figure 2B). The resulting LRP reflects the average amount of lateralization occurring as a result of central motor preparation.

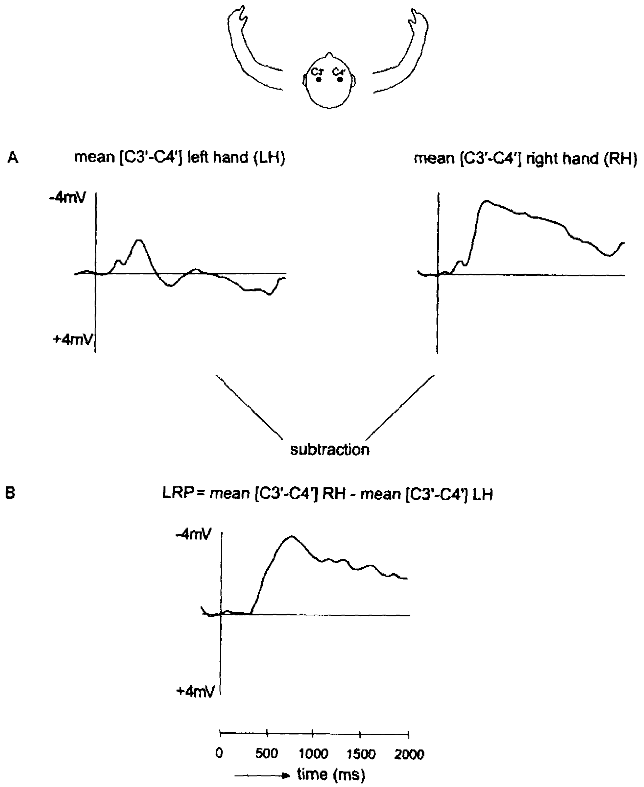


Figure 2. Derivation of the Lateralized Readiness Potential (LRP).

A First, on each trial, for each sample point, the difference is obtained between potentials recorded from electrode sites C3' and C4', located above the left and right motor cortices. These difference waveforms are averaged separately for trials in which the left versus the right hand is cued.

B Second, to cancel out lateralized potentials that are not specifically related to response preparation, the waveform obtained for the left-hand trials is subtracted from the waveform obtained for the right-hand trials. The resulting LRP reflects the average amount of lateralization occurring as a result of the motor preparation of response hands.

4.2. The LRP and partial information transmission

The LRP has been used in a variety of studies to assess the interaction between information processing and motor control (see Coles et al. 1995, for an overview). In particular, the LRP has been used to detect transmission of partial information between perceptual and motor processes (e.g., Coles 1989; De Jong et al. 1988; Miller and Hackley 1992; Osman et al. 1992; Smid et al. 1992). Some of the most compelling evidence that response preparation can start on the basis of partial stimulus information comes from studies in which the LRP technique is combined with a two-choice reaction go/nogo paradigm (e.g., Miller and Hackley 1992; Osman et al. 1992; Smid et al. 1992). In this paradigm, one attribute of a stimulus indicates a left- or right-hand response, while another attribute of the same stimulus indicates whether or not the response has to be given. The distinction between response hands is usually determined by an easily identifiable stimulus attribute while the go/nogo distinction is determined by a more difficult to discriminate stimulus attribute. For example, Miller and Hackley (1992) presented individuals with large and small Ss and Ts, and assigned these stimuli to left and right hand responses, or nogo reactions. Letter shape determined left versus right response hand, and letter size indicated whether the response should be given or withheld. The idea behind the paradigm is that if response preparation begins as soon as stimulus information is extracted, the stimulus attribute that becomes available early during the perceptual analysis (i.e., shape) could be used to prepare a response hand before the slower attribute (i.e., size) becomes available to distinguish between go/nogo. The critical predictions in the Miller and Hackley study concerned the presence of an LRP on nogo trials. If shape information is used to differentially activate response hands before the stimulus size is fully analyzed, one expects to observe an LRP on both go and nogo trials. The results show that, indeed, an LRP initially develops on nogo trials at about the same latency as on go-trials, but after some time returned to baseline in the absence of an overt response. This indicates that partial stimulus information activated the correct response hand before complete stimulus information became available to determine whether go or nogo was the correct reaction. Similar results were obtained independently by Osman et al. (1992), and by Smid et al. (1992), who used the same experimental paradigm but different stimulus sets. An important finding in the Osman et al. (1992) study was that they could separately manipulate the moment at which an LRP started to develop, and the moment at which the go and nogo LRP started to diverge. This clearly indicates that the LRP is differentially sensitive to the time course of the processes that lead to response hand selection and to the time course of the processes that lead to the go/nogo distinction.

Taken together, these studies provide strong evidence that the LRP is a real-time measure of the selection and preparation of motor responses. Moreover, they show that preliminary stimulus information is transmitted to the motor system, and used for response selection before complete stimulus information is available. This implies that, when combined with the two-choice go/nogo paradigm, the LRP provides an index of the relative moments in time at which different aspects of a stimulus become available for response selection.

4.3. The N200

A second ERP component that has recently been used to examine the time course of language-related processes is the N200. The N200 is a negative going potential, mainly distributed over fronto-central electrode sites, which develops around 200 ms after stimulus onset in experimental situations where a response needs to be withheld. Although the functional significance of the N200 is not as clear-cut as is the case for the LRP, a number of reports have linked the N200 to response inhibition processes. Electrophysiological recordings from prefrontal cortex in monkeys have demonstrated that during the performance of a go/nogo task, a N200 response occurs on nogo relative to go trials (Sasaki, Gemba, and Tsujimoto 1989). Moreover, Sasaki, Gemba, and Tsujimoto (1989) demonstrated that response inhibition could be induced on go trials by stimulating the prefrontal cortex of the monkey at the latency where an N200 response occurred on nogo trials. These results suggest that the N200 reflects, at least in part, response inhibition processes in prefrontal cortex. Thorpe and colleagues (1996) applied this characteristic of the N200 to examine the time course of visual processing. In their study, participants viewed pictures of complex visual scenes and were asked to respond only in cases where an animal was present in the scene. When comparing ERPs elicited on go and nogo trials, an enhanced negativity occurred on nogo relative to go trials, this negativity peaking at around 150 ms after picture onset. The authors interpreted this potential as an N200, and argued that in the context of a go/nogo paradigm, the peak latency of the N200 can be used to indicate the moment at which sufficient information is available to inhibit a response. On the basis of this interpretation, they concluded that at around 150 ms after stimulus onset, sufficient visual information was available to know whether or not an animal was present in the scene.

5. Electrophysiological evidence on the time course of speaking

5.1. Semantic retrieval as the initial processing stage

Applying the LRP logic to the study of spoken word production, Van Turennout, Hagoort, and Brown (1997) examined the relative moments at which semantic and phonological information is retrieved during word production. An illustration of their experimental paradigm is presented in Figure 3. The main experimental task was picture naming. In addition, on half of the trials subjects performed a semantic-phonological classification task before producing the word. The classification task consisted of the conjunction of a go/nogo decision and a left- or right-hand response. In this example, response hand was determined by the semantic classification, and the phonological classification determined whether or not a push-button response should be given. The logic behind the procedure is as follows. First, it is assumed that the semantic and phonological properties of the word that are required to perform the classification tasks become available automatically via the speech production system. If, during picture naming, semantic re-

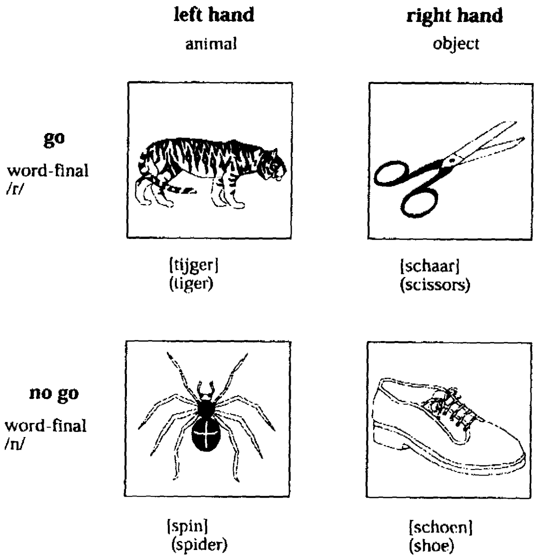


Figure 3. Example of the choice-reaction go/nogo paradigm using a semantic/phonological categorization task. In the figure, the picture names are shown in Dutch and English below the pictures. The four pictures depicted here represent separate trials for the four experimental conditions. An animal cues a left-hand response, and an object cues a right-hand response. The response has to be executed if the picture name ends with an /r/ (go trials), but is withheld if it ends with an /n/ (no-go trials). After Van Turennout et al. (1997).

trieval precedes the retrieval of phonological form, the results of the semantic classification will be transmitted to the response system earlier than the results of the word-initial phoneme classification. In this case, preparation of the response hand can start on the basis of semantic information before phonological information informs the subject whether to respond. As a consequence, an LRP should develop not only for go-trials, but initially also for nogo trials, without an overt response. The early availability of semantic information enables response preparation, but when information about the word's phonological form becomes available, this then overrules further response preparation on the nogo trials. This is exactly the pattern of results that was observed (see Figure 4A). In parallel with the development of an LRP on go trials, an LRP developed on nogo trials for a short period of time, suggesting a temporal advantage of semantic information over phonological information. The early available semantic information served as partial information, and therefore response preparation could start before sufficient phonological information was available to complete the go/nogo analysis.

A possible concern could be that both types of information are retrieved at the same moment during word production, but that because of the task configuration, the response hand is always selected before the go/nogo decision is made. Therefore, to validate the logic behind the paradigm, the task assignment was reversed in another condition. In this task configuration the response hand was determined by phonology and go/nogo was determined by semantics, testing the early use of phonological information. Earlier LRP studies had shown that in a choice reaction go/nogo task subjects assign priority to the extraction of stimulus information that can be used to select a response hand (Coles et al. 1995), which in this case is the phonological information. Nevertheless, if semantics is indeed retrieved before phonology, then an LRP should develop only on go-trials, and not on nogo trials. Indeed, the data showed that whereas an LRP was present on go trials, no significant LRP was observed on nogo trials (see Figure 4B). The absence of an LRP on nogo trials indicates that, on these trials, phonological information did not affect response preparation. Phonological information started to activate response hands only after the semantically based go/nogo distinction had been made. One of the important aspects of this experiment is that subjects were focused on the early use of

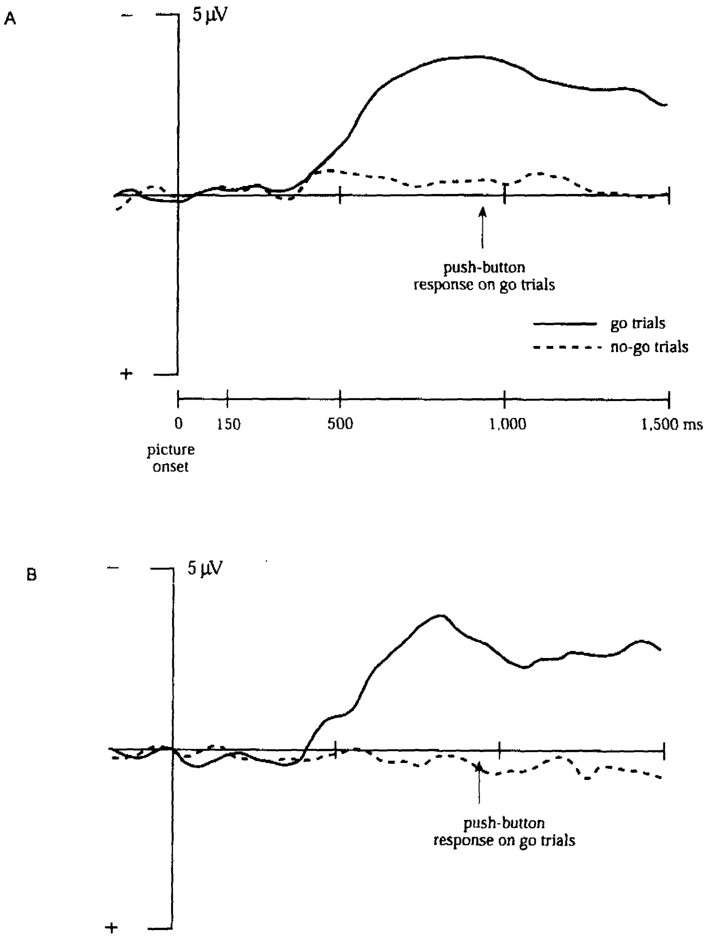


Figure 4. **A** Grand averaged LRPs on go and nogo trials. The semantic decision determined response hand; the word-final phoneme decision determined go/nogo. The shaded area shows the time interval in which the go and nogo LRPs were significantly different from baseline but not from each other.

B Grand averaged LRPs on go and nogo trials for the experiment in which the semantic decision determined go/nogo and the word-final phoneme decision determined the response hand. No significant lateralization of the readiness potential was obtained on nogo trials. After Van Turennout et al. (1997).

phonological information for the rapid selection of response hand. Given the task configuration, there was every reason for the subjects to assign priority to retrieving the phonological information of the noun to select a response hand, before retrieving the semantic information. However, the data demonstrated that phonological information was not available to be used as partial information to activate response hand. Apparently, even if subjects are encouraged to use phonological information earlier than semantic information, they do not. These findings indicate that semantic information influences response preparation at an earlier moment in time than phonological information, and rule out the possibility that the early response preparation observed on nogo trials was due to strategic control over the use of partial information.

Using a similar experimental paradigm, but with German stimulus materials and subjects, Schmitt, Münte, and Kutas (2000) replicated the LRP findings on semantic and phonological processing reported by Van Turennout et al. (1997). Interestingly, in addition to effects on response preparation as measured by the LRP, Schmitt and colleagues reported differential effects of response inhibition as measured by the N200 on nogo trials. They found that when the go/nogo decision was contingent on semantic information the N200 peaked about 90 ms earlier than when the go/nogo decision was contingent on phonological information. This suggests that semantic information was retrieved, and available to the response system about 90 ms earlier than phonological information. These results nicely parallel the LRP data, and again demonstrated that during speech production semantic processing precedes phonological encoding.

Following the same logic, Schmitt et al. (2001a) examined the temporal relation between semantic and syntactic processing. According to WEAVER++, semantic information is not only available prior to phonological information, but also prior to syntactic information. Alternatively, semantic and syntactic information might become available simultaneously. Schmitt et al. (2001a) aimed to disassociate between these two accounts using the following procedure. Subjects were involved in a picture-naming task and in addition, they made go/nogo decisions based on an object's semantic specifications (is the depicted object heavier or lighter than 500 gram) and on a syntactic feature of the depicted noun (is the noun's grammatical gender male or female). The results showed that when semantics determined response hand, a nogo LRP was present between 452 and 540 ms after picture onset. This suggests that the response was prepared on the basis of semantic information, while syntactic information was not yet available to make the go/nogo decision. Importantly, when syntax determined response hand, an LRP was observed only on go trials, and not on nogo trials. The N200 data showed a similar pattern of results: When the go/nogo decision was contingent on semantic information, the average peak latency of the N200 effect was 73 ms earlier than when it was based on syntactic information. Thus, consistent with time course predictions derived from WEAVER++, these results suggest that semantically driven processes onset earlier than syntactically based processing.

Although the results described above are consistent with the view that semantic processing precedes syntactic and phonological encoding, they do not necessarily imply strict seriality of processing stages. It could very well be that, although lemma and word-form retrieval are triggered by semantic activation, these retrieval operations do not wait until a full semantic analysis of an object has been completed. To address this issue, Abdel Rahman, Van Turennout, and Levelt (submitted) examined whether phonological encoding in picture naming is mediated by basic semantic feature retrieval, or proceeds independently. According to decompositional views of semantics (e.g., Bierwisch and Schreuder 1992; Dell et al. 1997) object naming is mediated by sets of basic semantic features, which in combination constitute the meaning of a word. In contrast, in WEAVER++ lexical meanings are represented in a non-decompositional fashion, that is, as entities without internal structure. This means that retrieval of distinct semantic features is not essential for naming, and can, in principle, proceed in parallel to word form encoding, as long as the relevant lexical concept has been retrieved.

To distinguish between serial and parallel processing with the LRP in a two-choice go/nogo paradigm, Abdel Rahman and colleagues manipulated the retrieval latency of the basic semantic feature animacy, and examined whether this manipulation affected the time course of phonological encoding. In a manual two-choice go/nogo task, pictures of objects were classified according to both semantic and phonological information. The manual choice response (i.e., left or right response hand) was based on an animacy classification whereas the go/nogo decision was based on an initial phoneme classification. To selectively manipulate the duration of animacy retrieval a task mixing procedure was introduced. The manual response was based on either the animacy classification throughout the entire block of trials, or was randomly alternated by an additional semantic classification (i.e., does the object occur in or outside the water). In the alternating case a color cue indicated whether the decision had to be based on animacy or on inside/outside the water. The logic behind this manipulation is as follows. If phonological encoding is mediated by semantic feature retrieval, then its onset should vary as a function of the speed with which a semantic feature is retrieved. In contrast, if the two processes can proceed in parallel, the phonological code retrieval should not be affected by the speed of semantic processing. The results showed that a nogo LRP was present in the blocked classification mode. This replicated earlier findings showing that semantic features are typically retrieved faster than phonological information. However, no sign of early response preparation was found in the mixed classification mode, indicating that phonological encoding can proceed while semantic feature retrieval is not yet completed. These results suggest that a basic semantic feature like animacy, although usually retrieved prior to name phonology, is not essential for the initiation of phonological encoding. This means that lemma retrieval and word form encoding do not necessarily depend on the retrieval of pre-defined semantic attributes. Simultaneous activation of semantic and phonological features is in clear contrast with a strictly serial account, and consistent with a parallel account of semantic and phonological processing. In WEAVER++, the selection of a concept always precedes phonological encoding. Therefore, the data seem to be at odds with predictions from WEAVER++. However, in WEAVER++ concepts are represented in a non-decompositional way. That is, lexical concepts are represented as undivided wholes, and distinct semantic features of the concept are retrieved through labeled links to other concepts (for example, DOG 'is an' ANIMAL). This means that, after a lexical concept has been selected, related semantic features can be retrieved in parallel with lemma retrieval and phonological encoding. Therefore, in principal, WEAVER++ allows for word form encoding to start without having a core semantic feature such as animacy available yet.

5.2. *Lemma retrieval precedes phonological encoding*

In another series of experiments, Van Turennout, Hagoort, and Brown (1998) investigated the time course of lemma retrieval and phonological encoding. According to WEAVER++ lemma retrieval is strictly separated from phonological encoding in time. Using the LRP go/nogo paradigm in combination with noun-phrase production, Van Turennout et al. (1998) demonstrated that if a word's syntactic gender, which is represented at the lemma level, is mapped onto response hand while the go/nogo decision is determined by a word's initial phoneme, an LRP developed on both go and nogo trials. When task assignments were reversed, an LRP developed on go trials only. Consistent with the WEAVER++ model, these results clearly demonstrate that speakers retrieve lemma and phonological information in a fixed temporal order: a word's syntactic properties are retrieved before its phonological properties, but the reverse is not possible: speakers do not activate a word's phonology without having previously retrieved its syntax.

The length of time interval during which syntactic but no phonological information was available could be estimated by comparing go and nogo LRPs (see Figure 5). Two time points are of interest here. First, the go and nogo LRPs started to develop at about 370 ms after picture onset. Thus, at that moment syntactic gender was available to select the correct response hand. Second, at about 410 ms after picture onset the go and nogo LRPs diverged sharply.

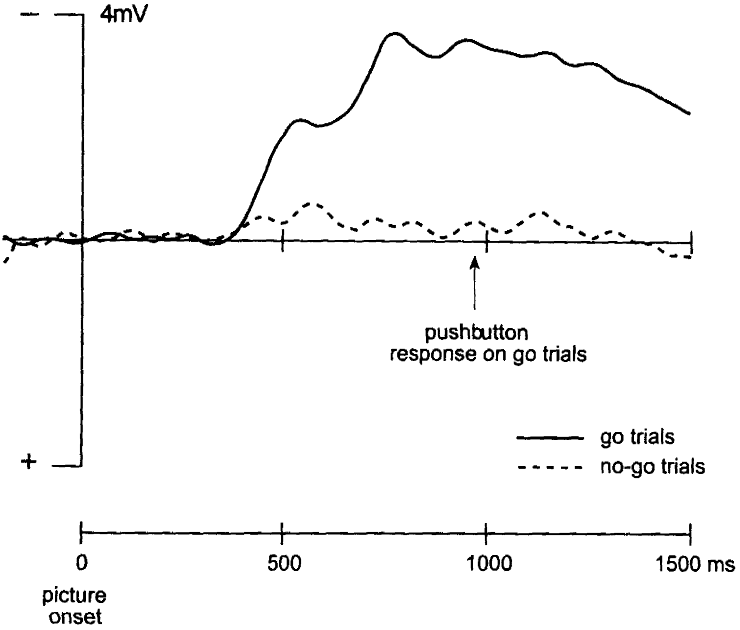


Figure 5. Grand averaged LRPs on go trials and nogo trials. The syntactic gender decision determined response hand; the word-initial phoneme decision determined go/nogo. Significant lateralization of the readiness potential was obtained both on go and on nogo trials from 370 ms after picture onset. The shaded area shows the time interval in which the go and the nogo LRPs were significantly different from the baseline, but not from each other. The right border of the shaded area marks the moment (410 ms) at which phonological information leads to the termination of the syntactic response preparation on nogo trials. After Van Turennout et al. (1998).

While the go LRP continued to develop, the nogo LRP gradually returned to the baseline. This indicates that there was already enough phonological information available 40 ms after LRP onset to make the go nogo distinction. Thus, in noun phrase production it takes only about 40 ms to retrieve a word's initial phoneme once its syntactic gender has been retrieved.

5.3. Seriality in phonological encoding

So far, we have been discussing data on the relative time course of distinct stages of lexical access in speech production. However, the LRP paradigm has also been used to obtain evidence on the time course of information retrieval within a single processing stage. In their 1997 study, Van Turennout and colleagues demonstrated that the duration of a nogo LRP was dependent on the position of the critical phoneme in a word. When the go/nogo decision was based on a word's initial phoneme, a nogo LRP developed on the basis of semantic information for about 40 ms. However, when the go/nogo decision was based on a word's final phoneme, a semantically based nogo LRP was present for a period of 120 ms (see Figure 4A). This prolongation of the duration of the LRP suggests that phonological encoding proceeds in a left-to-right manner (Wheeldon and Levelt 1995), with information about a word's initial phoneme becoming available about 80 ms earlier than information about a word's final phoneme. This result was obtained for words with an average length of 1.5 syllables. Most likely, the retrieval time of the non-initial segments will vary with word length.

5.4. Time estimates

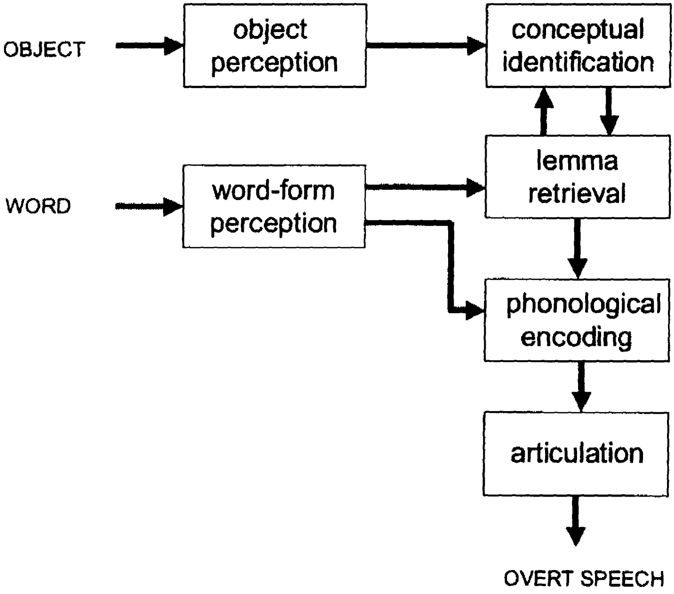
Taken together, the electrophysiological data provide strong support for the WEAVER++ model of speech production. In addition, the combined LRP and N200 data provide detailed time estimates of the duration of the distinct processing stages. In sum, when subjects are involved in picture naming, the selection of a lexical concept takes place around 150-225 ms after picture onset, syntactic encoding (i.e. lemma retrieval) in the time window of 225 and 275 ms, and phonological encoding between 275 and 400 ms (see also Hagoort and Van Turennout 1997; Levelt 2001). Depending on task context, however, additional semantic (and perhaps also additional syntactic) processing continues after phonological retrieval, arguing against a strictly sequential architecture, and in favor of a more cascaded architecture of the speech production system (Abdel Rahman, Van Turennout, and Levelt submitted).

6. The time course of information access in single word comprehension

In essence, language comprehension is about mapping sounds or orthographies onto meaning. Blueprints of the listener and the reader assume that word form processing triggers the retrieval of syntactic and semantic word information which gets integrated into the utterance context (see Cutler and Clifton 1999 for listening; see Perfetti 1999 for reading). The final result is a message-level representation of the overall meaning of the utterance.

Although most of psycholinguistic research has focused on language comprehension rather than language production, strangely enough the time course of lemma and semantic retrieval in single word comprehension is a largely uncharted area. Models of word recognition implicitly assume that upon word form retrieval, syntactic and semantic information associated with a particular word form are immediately available. Although most models of language comprehension include assumptions about temporal properties of information between phonetic, phonological and lexical processing levels, none of these models contain time course predictions for the retrieval of the different levels of lexical and semantic information. The only model that makes such predictions is WEAVER++, which was originally designed as a model for speech production.

In WEAVER++ it is assumed that language production and comprehension share common levels of semantic and lemma representations, but have distinct levels of form representations.



WEAVER++: after Roelofs (in press, *Psychological Review*)

Figure 6. Illustration of the interaction between word production and comprehension in WEAVER++.

In WEAVER++, incoming word form information enters a form level for comprehension. Activation of a representation at this form level spreads to the lemma level, which gives access to syntactic information. From the lemma level, information spreads to the conceptual level to allow the retrieval of word meaning. The flow of information between levels proceeds over time (see Levelt, Roelofs, and Meyer 1999). Under the assumption that the comprehension system relies on the same lemma and conceptual levels, the time course of information flow between levels for comprehension should be the reverse as the one for production (see Figure 6). For example, phonological analysis should be accomplished first, followed by lemma retrieval, followed by the retrieval of the lexical concept.

These time-course issues in comprehension have been addressed in a series of recent ERP studies, using LRP and N200 measures as introduced above.

6.1. Phonological versus semantic encoding during listening

Rodriguez-Fornells and colleagues (2002) investigated whether phonological information is available prior to semantic information, as predicted by WEAVER++. Behavioral studies have indicated that lexical candidates can be activated on the basis of word-initial phonological information (e.g., McQueen, Norris, and Cutler 1994; Zwitserlood 1989), suggesting that word meaning might already be activated after only the beginning of a word has been heard. Rodriquez-Fornells et al. focused on the N200 component as a measure for the availability of phonological and semantic information during spoken word comprehension. Subjects listened to sequences of nouns and had to carry out a left hand/right hand response together with a go/nogo decision. As in a typical two choice go/nogo paradigm, in one condition (go/nogo=semantics) participants were asked to respond (go trials) or to refrain from responding (nogo trials) depending on the semantic category of the stimulus (e.g., go=animal, nogo=object). In this condition the response-hand assignment was defined by the phonological properties of the stimulus (one hand if the initial phoneme was a consonant, the other hand if it was a vowel). In the other condition (go/nogo=phonology) the response contingencies were reversed, i.e. response preparation was based on semantics and the go/nogo decision was based on phonological information.

Figure 7 displays the topographic scalp distribution of the N200 effects. The left column depicts an early time window (480-520 ms after word onset). It shows that over frontal scalp sites the N200-effect is clearly visible for phonology but not for semantics. The right column shows a later time window (570-610 ms after word onset). In this window the phonological N200-effect has disappeared and the semantic N200-effect is fully visible. That is, the moment in

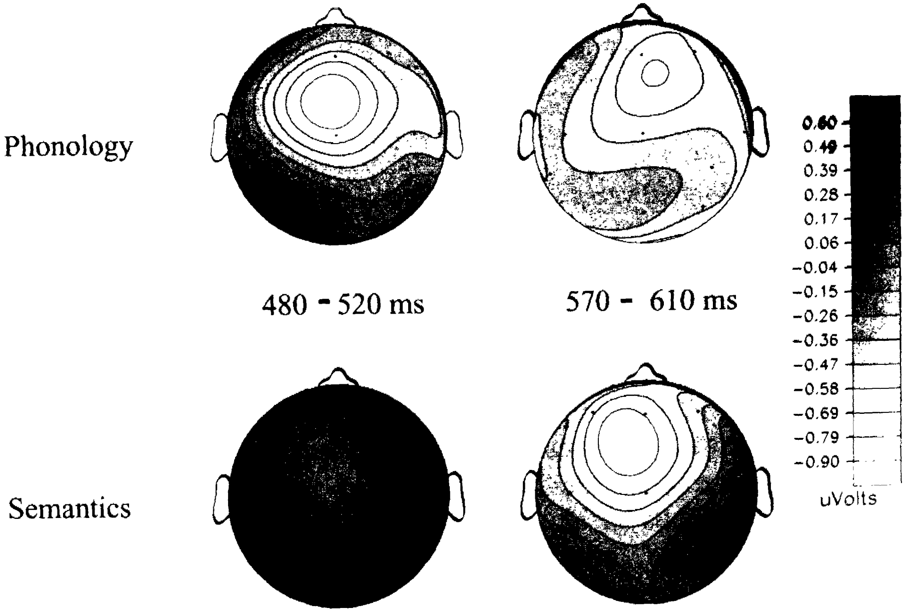


Figure 7. Scalp distribution of the N200 during listening to words. Shown are topographic mean voltage maps for two time windows. Left: 480-520 ms after word onset (time window for the phonological N200 effect). Right: 570-610 ms after word onset (time window for the semantic N200 effect).

time at which the nogo and go waveforms maximally deviate is 90 ms earlier when the phonological information determines go/nogo than when semantic information determines go/nogo. From these results it can be inferred that during spoken word processing phonological information becomes available about 90 ms prior to semantic information. These results are in line with findings from lexical decision ERP studies in reading (Bentin et al. 1999). Importantly, for the retrieval of semantic and phonological information the temporal relation of N200 peak latencies was reversed compared to N200 results in single word production. As we discussed above, several ERP studies on object naming have demonstrated that semantic retrieval precedes phonology by 40-160 ms. The ERP comprehension data together with the production data provide support for the WEAVER++ model.

6.2. Syntactic versus semantic encoding during listening

In addition to the relative time course of semantic and phonological retrieval during single word processing, Schmitt et al. (2001b) investigated the time course of the information flow between syntactic and semantic processing levels in listening. Models like WEAVER++ would seem to predict that syntactic information is available prior to semantic information (but see later). Again, the N200 component was used to compare semantic and syntactic information access. Subjects listened to sequences of nouns and had to carry out a two choice go/nogo decision. In one condition (go/nogo=semantics) participants were asked to respond or to refrain from responding depending on the semantic category of the stimulus (e.g., go=animal, nogo=object). In this condition the response-hand assignment was defined by the syntactic properties of the stimulus. In the other condition (go/nogo=syntax) the response contingencies were reversed, i.e. response preparation was based on semantics and the go/nogo decision was based on syntactic gender information. Figure 8 shows the nogo-go difference waves for both conditions. The observed negativity in the difference waves is the N200 effect. The N200 effect peaked earlier in the go/nogo=semantics condition than in the go/nogo=syntax condition by a significant 69 ms. This finding clearly shows that semantic information became available prior to syntactic information. The observed time shift of peak latencies is comparable with the earlier described shift of syntactic and semantic N200 effects during object naming (80 ms, Schmitt et al. 2001a, b).

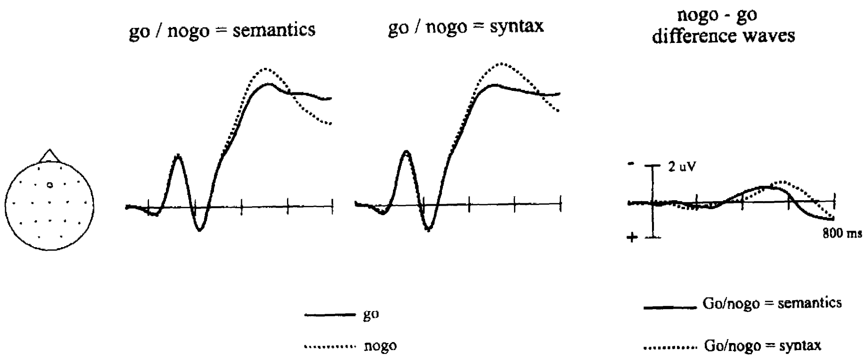


Figure 8. Grand average ERPs from the syntactic vs. semantic listening experiment on go and nogo trials in the go/nogo=semantics condition (left column), and the go/nogo=syntax condition (middle column). The ERPs were time-locked to speech onset. Both conditions are associated with a frontal negativity that is larger for nogo than for go trials. In the right column, the 'nogo minus go' difference waves for the two conditions are shown superimposed. Displayed are data from the frontal electrode site Fz.

6.3. *Syntactic versus semantic encoding during reading*

Müller and Hagoort (2001) investigated the time course of syntactic and semantic decoding during reading. These authors analyzed both LRP and N200 effects in relation to the retrieval of lemma and semantic information. As is the case for listening, WEAVER++ would seem to predict that, in reading, lemma information precedes semantic information (see Figure 6). In this experiment, participants read single Dutch nouns presented on a computer screen and performed a two choice go/nogo task. For one group of participants the syntactic gender of the word indicated the response hand (left/right) and the semantic category of the word determined whether the response had to be executed or not (go/nogo). Another group of participants received reversed instructions, so that semantic category indicated response hand and syntactic gender determined response execution. LRPs were derived for the go- and nogo-conditions of both instruction groups. Under the assumption that syntax precedes semantics in comprehension, the following LRP pattern was expected: (i) When response preparation is contingent on syntactic information and the go/nogo decision is contingent on semantic information, a nogo LRP should evolve due to early availability of syntactic information. (ii) When response preparation is based on semantic information, the nogo LRP should be absent. The reason for this is that response preparation starts after syntactic information has been able to instruct the go/nogo decision. However, the LRP results that were obtained showed exactly the opposite pattern. When semantics specified response hand and gender determined response execution, a significant deviation from baseline was found for nogo-trials, starting at 484 ms after stimulus onset. It ran parallel to the standard LRP effect on go-trials until 524 ms and then returned to baseline without causing an overt response. This indicates that preparation of the response hand (based on semantics) occurred before gender information was able to instruct the system not to respond. A nogo-LRP was not observed when gender specified response hand and semantics determined response execution. The data indicated that for comprehension in reading, as for comprehension in listening and for picture naming, semantics is available earlier than syntactic information. This finding was further supported by the N200 effects in the same study.

In sum, whereas the finding for phonology versus semantics supports the model of Levelt and colleagues (1999) and the underlying WEAVER++ assumptions, the findings that semantics precedes syntax in both listening and reading seems to be at odds with the model. However, a simulation of the Müller and Hagoort (2001) LRP data in the WEAVER++ model (Roelofs personal communication) showed exactly the pattern of results that was obtained. According to Roelofs, this seemingly contradictory outcome can be explained by the fact that, in WEAVER++ lexical concept nodes connect to a much larger network than lemma nodes. This means that, given the information flow in the model, activation is built up faster for semantic feature nodes than for syntactic feature nodes. As a consequence, even when lemma selection precedes lexical concept selection, a semantic feature can be activated and retrieved earlier than a syntactic feature. This is compatible with the LRP and N200 findings that lemma-related information is activated later in time than concept-related information. The difficulty in testing time course predictions from models like WEAVER++ lies in the fact that in network models are empty nodes. This means that, for example, lemma and concept nodes can only be probed indirectly through its related gender or semantic category nodes. This provides a challenge for future experiments testing the temporal dynamics of WEAVER++.

7. Concluding remarks

In this chapter we presented electrophysiological data on the time course of the information flow during single word processing in both speaking and listening/reading. In both cases at least three completely different types of information are at stake, and have to be retrieved with high speed and accuracy. These information types concern the sound pattern (or their orthographic correlates) of words, their syntactic specifications (lemma) and word meanings.

Before turning to conclusions we need to address two concerns related to the use of the two-choice go/nogo paradigm in language research. A first concern when using picture classification tasks to probe speech-related processes is that critical features could be retrieved from different linguistic representations than the ones used in speech production. However, picture naming is one of most commonly used tasks in the study of speech production because it is assumed to engage the same processes as the ones that occur naturally in speaking (see Glaser 1992 for an overview). Thus, the same linguistic representations are accessed when naming pictures or speaking naturally. Since in all of the experiments described above pictures were named either implicitly or explicitly, it seems very unlikely that the picture classification tasks activated different linguistic representations than the ones used for picture naming, and thus, natural speech. For a detailed account of this issue see Schmitt, Münte, and Kutas (2000). A second concern when using classification tasks is that they involve information retrieval as well as choice-response selection. As a consequence, the LRP and N200 data provide time estimates of retrieval time *plus* additional processes associated with response selection. This means that, when using complicated decision tasks, one needs to take care that response selection processes do not differ between conditions. This can be accomplished in pilot studies (see for example Abdel Rahman, Van Turennout, and Levelt submitted) or through consistency in results across different task configurations. For example, validation for the assumption that the LRP reflects temporal estimates of information retrieval comes from a comparison between LRP results of a study in which word-initial phoneme decision was combined with semantic decision (Van Turennout, Hagoort, and Brown 1997), and LRP results from a study in which word-initial phoneme decision was combined with syntactic decision (Van Turennout, Hagoort, and Brown 1998). The LRP data showed that in the semantic configuration, word-initial phonological information became available for response preparation at 400 ms after picture onset. In the syntactic configuration, the moment that the go and nogo waveforms started to diverge due to the availability of the noun's initial phoneme was at 410 ms. Even though different subjects participated in the two studies, and the pictures were also different, the moment at which phonological information became available is strikingly similar. This suggests that indeed the derived LRPs are probing automatic information retrieval during language processing.

In language production models (e.g., Dell 1986; Caramazza 1997; Levelt 1989; Levelt, Roelofs, and Meyer 1999) it is generally assumed that the information flow is from concept to lemma to sound. This claim is strongly supported by the electrophysiological data on speaking that have been obtained in recent years and were discussed above. The LRP and N200 data even allow for a fairly fine-grained estimation of the relative timing of the retrieval/selection of the three different information types in speaking. However, the data also showed that the time course of information retrieval at these levels is not fixed. Instead, the exact temporal profile of information retrieval is flexible and open to influences from task or input context. Thus, it remains to be seen whether the temporal profile for single word production in a picture-naming paradigm can be generalized to the more common situation of producing words in the context of a larger utterance/message.

For single word comprehension the situation is less clear. First, in language comprehension research the division of labor has been between researchers studying word recognition and researchers investigating sentence processing. Models of word recognition are not explicit about the temporal profile of the retrieval processes beyond accessing word form information. Sentence processing researchers start with the availability of semantic and syntactic information. In-between is the gap that connects word form access to syntactic and semantic integration of lexical information into the context. What is lacking is information about the temporal profile of lemma and concept-related retrieval processes once word form information is accessed. Surprisingly enough, the only model with a time course prediction for word comprehension originates from the domain of language production (i.e. WEAVER++). This model predicts the reversed information flow for comprehension, compared to speaking. That is, in comprehension the information flows from word form to lemma to concept. The LRP and the N200 data that we discussed above showed a more complicated pattern. Although word form was always preceding semantic information, semantic information was retrieved before syntactic information. This is compatible with a number of architectures. One possible architecture is that word forms activate lemmas and lexical concepts in parallel, with differential retrieval times for both. Alternatively, the data are consistent with the assumption that a concept has to be selected before a lemma can be retrieved. This assumption, however, does not seem to be compatible with the finding that we can retrieve lemma information for Jabberwocky sentences for which no lexical concepts are available (e.g., Münte, Matzke, and Johannes 1997). Finally, as WEAVER++ simulations show, despite their seeming counterevidential nature, the data are even compatible with a model that requires lemma selection before concept retrieval. Clearly, additional studies are required to determine which of the possible architectures for single word comprehension is the most likely one.

In the meantime, the time course data that were obtained are not without significance for our views on language comprehension. For instance, in a recent model of comprehension based on ERP data, Friederici (2002) has claimed that in sentence processing there is a first phase from 100-300 ms in which the initial syntactic structure is formed on the basis of lemma information (i.e. word category). Only in a later phase (300-500 ms) lexical-semantic processes take place. These claims are based on the latencies of the ERP effects for violations of word category and lexical-semantics, respectively, in a sentence context. However, the consistent finding that in single word comprehension semantic information is earlier available than lemma information is in clear disagreement with the claims put forward by the sentence comprehension model by Friederici (2002). To account for this inconsistency between data and theory, one could make the additional assumption that, although semantic information is available earlier than lemma information, it is integrated later. However, for all we know about the incremental nature of language processing, this seems a highly implausible assumption. This illustrates that information on the temporal profile of single word comprehension is not without consequences for higher order models of sentence comprehension.

In conclusion, when words come to mind either through an idea or through sound, time plays a crucial role in connecting sounds and meanings. This was first realized by Donders (1868), who measured the duration of mental processes with the help of the 'noematachograph' and other mechanical instruments. Today we can directly record the brain signals related to mental events of interest. As we showed, this results in an even more fine-grained temporal profile than was possible with the precision instruments in Donders' times.

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