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The Time Course of Grammatical and Phonological Processing During Speaking: Evidence from Event-Related Brain Potentials

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Motor-related brain potentials were used to examine the time course of grammatical and phonological processes during noun phrase production in Dutch. In the experiments, participants named colored pictures using a no-determiner noun phrase. On half of the trials a syntactic–phonological classification task had to be performed before naming. Depending on the outcome of the classifications, a left or a right push-button response was given (go trials), or no push-button response was given (no-go trials). Lateralized readiness potentials (LRPs) were derived to test whether syntactic and phonological information affected the motor system at separate moments in time. The results showed that when syntactic information determined the response-hand decision, an LRP developed on no-go trials. However, no such effect was observed when phonological information determined response hand. On the basis of the data, it can be estimated that an additional period of at least 40 ms is needed to retrieve a word's initial phoneme once its lemma has been retrieved. These results provide evidence for the view that during speaking, grammatical processing precedes phonological processing in time.

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. The present study is concerned with the temporal parameters of the processes that underlie speaking. The main focus is on the time course of grammatical and phonological encoding in noun phrase production. Two experiments were

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designed to examine whether grammatical processing precedes phonological processing in time. We use event-related brain potentials (ERPs) to tap into grammatical and phonological processing as it proceeds in real time.

PROCESSING LEVELS IN SPEECH PRODUCTION

In describing the processing mechanisms underlying the transformation of a thought into speech, theories of speech production usually distinguish between conceptual, grammatical, and phonological processing levels (Bock, 1982; Bock & Levelt, 1994; Butterworth, 1989; Dell, 1986; Garrett, 1975, 1976, 1980; Kempen & Huijbers, 1983; Levelt, 1989). At the conceptual level a conceptual structure, often called the message (e.g., Garrett, 1975; Levelt, 1989), is abstracted from the many aspects of an idea. The message represents the speaker's intention and specifies the content of the utterance. During grammatical processing, the conceptual structure is translated into a linguistic representation. The conceptual structure drives the activation and selection of the appropriate word representations in the mental lexicon. These representations are often called *lemmas* (Kempen & 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 & 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 (see for a detailed description of grammatical encoding Bock & Levelt, 1994; 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 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, 1988; Levelt, 1989; Levelt & Wheeldon, 1994; Meyer, 1992; Meyer & Schriefers, 1991; Shattuck-Huffnagel, 1979, 1983). In the present study we focus on the separation between the grammatical and phonological processing level.

Empirical support for the distinction between a grammatical and a phonological processing level originates from the analysis of speech errors observed in natural speech (cf. Garrett, 1975, 1980, 1988; MacKay, 1970) and elicited under experimental control (see, for example, Bock & Eberhard, 1993). Clear evidence for a distinction between lemmas and word forms comes from the tip-of-the-tongue phenomenon (Brown & McNeill, 1966; Brown, 1991; Vigliocco, Antonini, & Garrett, 1997), from studies of language impairment [Butterworth, 1989; see Garrett (1992) for an overview], and from experimental studies (Kempen & Huijbers, 1983; Levelt, Schriefers, Vorberg, Meyer, Pechmann, & Havinga, 1991; Levelt & Maassen, 1981; Schriefers, Meyer, & Levelt, 1990).

Although there is ample evidence for the existence of separate conceptual–semantic, syntactic, and phonological processing levels in speech production, much less is known about the temporal parameters under which these processes operate. The temporal coordination of the separate processing levels is of crucial importance for the production of fluent speech. This becomes apparent when one considers the fast speech rate [on average speakers produce two to three words per second (cf. Maclay & Osgood, 1959; Levelt, 1989)] and the high level of fluency that speakers are able to achieve. In order to produce such fluent speech, the processing components of the production system need to be simultaneously active (Dell, 1986; Kempen & Hoenkamp, 1987; Levelt, 1989). In stage theories of speech production, the parallel activity at the conceptual, syntactic, and phonological levels is combined with seriality. This means that although the different processing components are simultaneously active, each of the components is assumed to work on a different part of the sentence (Dell, 1986; Garrett, 1976; Kempen & Hoenkamp, 1987; Levelt, 1989). According to these theories, the processing of a fragment at one level is guided by the level directly above it. With respect to the temporal parameters of grammatical and phonological encoding, this implies that the phonological form of a particular sentence fragment can be constructed only after the syntactic frame of that fragment has been built-up.[3]

The claim that during speaking grammatical processing precedes phonological processing in time has mainly been based on speech error data (Garrett, 1980, 1988; Dell, 1986) and by studies examining word order preferences (Bock, 1986; McDonald, Bock, & Kelly, 1993). However, these studies did not focus on time course questions, and the measures they used did not tap into the speech production process as it proceeds in time. The aim of the present research is to provide real-time evidence on the temporal parameters of grammatical and phonological encoding. We used noun phrase production as the primary experimental task because it involves both grammatical and phonological encoding. We apply the event-related brain

[3] Although it is generally agreed upon that the size of these sentence fragments should be small, and different between the levels, the exact size and the nature of the processing units at the separate levels are still unclear. For relevant evidence and discussions on this topic, See, for example, Bock (1982), Ferreira (1991), Ford and Holmes (1978), Kempen and Huijbers (1987), Levelt (1989), Levelt and Maássen (1981), Meyer (1996), and Schriefers (1992).

potential (ERP) technique to tap into these processes as they proceed in real-time. The ERP component we use is the lateralized readiness potential (LRP). First, we will describe the characteristics of the LRP, and then we will explain how this measure is used to provide insight into the time course of grammatical and phonological processing.

LATERALIZED READINESS POTENTIAL

The LRP is derived from the readiness or Bereitschafts potential (Kornhuber & Deecke, 1965). The readiness potential (RP) is a movement-related brain potential that occurs before a movement is executed. For hand movements, the RP is largest in amplitude at scalp sites overlying the motor cortex contralateral to the moving hand. The lateralized part of the RP has been shown to be related to the preparation for the execution of a specific movement (cf. Kutas & Donchin, 1974, 1977, 1980; Vaughan, Costa, & Ritter, 1968; Rohrbaugh, Syndulko, & Lindsey, 1976). To be able to use the lateralized motor potentials as a measure for specific response preparation, they have to be isolated from all other lateralized brain activity occurring at the scalp. To achieve this, the following two-step subtraction procedure has been used in experimental situations in which either a left-hand or a right-hand movement is executed in response to a stimulus (Coles, Gratton, & Donchin, 1988; De Jong, Wierda, Mulder, & Mulder, 1988). First, for each trial, the amount of lateralized activity is obtained by subtracting potentials recorded from above the left motor cortex from potentials recorded from above the right motor cortex. These differences are averaged separately for left- and right-hand trials. In the second step, the average lateralization obtained for the left-hand trials is subtracted from the average lateralization obtained for the right-hand trials. Lateralized activity that is not specifically related to response preparation will be the same on both left- and right-hand trials and will therefore be eliminated by the second subtraction. The resulting measure is the LRP, reflecting the average amount of lateralization occurring as a result of specific motor preparation (see for detailed description Coles, 1989; De Jong *et al.,* 1988).

The LRP has been used in a variety of studies to assess aspects of human information processing (see Coles, Smid, Scheffers, & Otten, 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; Dehaene, Naccache, Le Clec'H, Koechlin Mueller, Dehaene-Lambertz, Van de Moortele, & Le Bihan, 1998; De Jong *et al.,* 1988; Miller & Hackley, 1992; Osman, Bashore, Coles, Donchin, & Meyer, 1992; Smid, Mulder, Mulder, & Brands, 1992). An experimental paradigm in which it has been established that an LRP can develop on the basis of partial stimulus evaluation is the two-choice reaction go/no-go paradigm (e.g., Smid *et al.*, 1992; Osman *et al.*, 1992; Miller & Hackley, 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 results obtained in this paradigm consistently show that partial stimulus information can be used to select response hands before the stimulus has been fully identified. This means that an LRP can develop on the basis of partial information. As soon as perceptual and cognitive information relevant for response-hand selection is transmitted to the motor system, an LRP starts to develop, even if, on the basis of complete information, no overt response is given. As such, the LRP can be used to detect the relative moments at which distinct kinds of information become available for response preparation. However, some care has to be taken in interpreting the initial development of an LRP as an indication of the moment in time that information becomes available. Some evidence exists that in certain experimental conditions, the use of partial information for response selection can be strategically modulated (Gratton, Coles, & Donchin, 1992; Smid *et al.*, 1992; De Jong, Liang, & Laubert, 1994). This flexibility in transmission processes needs to be kept in mind when applying the LRP paradigm to investigations of time-course differences in cognitive processes.

The LRP go/no-go paradigm was recently used by us to study the time course of speech production (Van Turennout, Hagoort, & Brown, 1997). In the Van Turennout *et al.* study, the LRP was used to detect a separation in time between the availability of semantic and phonological information during picture naming. In addition to picture naming, a semantic–phonological classification of the picture had to be performed. Individuals were asked to respond with one hand for animate, and with the other hand for inanimate picture referents, a decision requiring the retrieval of semantic information. The decision whether or not to execute the response was determined by the word-initial phoneme, necessitating the retrieval of the phonological form of the picture name. During the performance of this task, ERPs were recorded from electrode sites located above the left and the right motor cortices, and LRPs were derived. The rationale behind the study was as follows: If, during picture naming, semantic activation precedes the retrieval of the sound pattern, the results of the semantic process will be transmitted to the response system earlier than the results of the phonological retrieval. In this case, preparation of the response hand can start before phonological information informs the individual about whether or not to respond. Exactly this pattern of results was observed. An LRP developed not only for go trials, but initially also for no-go trials, in the absence of an overt response. The early availability of semantic information enabled response preparation, but when information about the word's sound pattern became available, this then overruled further response preparation on the no-go trials. These results show that the LRP can be used to track the time course of processes involved in speech production, and they provide evidence for the claim that during picture naming there is an initial stage of semantic activation, followed by a stage of phonological encoding.

In the present study a similar paradigm will be used to investigate whether syntactic processing precedes phonological processing in time. The evidence for the distinctiveness of syntactic and phonological processing makes it plausible to assume that the output of these two stages can be transmitted separately to the response processes. On the basis of the results of the studies described above, we hypothesize that if the syntactic and phonological stages are not only distinct but also have a different time course, the output of these processes should be available for response preparation at separate moments in time. To initiate syntactic and phonological processing in speech production, we instruct individuals to produce noun phrases in response to colored pictures. In addition to the production task, a two-choice reaction go/no-go procedure is applied to distinguish between the moments at which syntactic and phonological information becomes available for response preparation. Before we turn to the details of the experimental paradigm, we will describe the syntactic processes involved in noun phrase production that are relevant for the present study.

NOUN PHRASE PRODUCTION

In Dutch noun phrases that contain an adjective, the adjective has to precede the noun. Dutch nouns usually have either one of two grammatical genders: common gender or neuter gender.[4] When produced with a definite article, a noun phrase is gender marked by the definite article of the noun, *de* for nouns of common gender, and *het* for nouns of neuter gender (e.g., *de rode bank,* the red couch; *het rode bed,* the red bed). When a noun phrase is produced without a definite article, gender is marked by the adjectival inflection. For common gender, the adjective stem carries the suffix *e,* whereas for neuter gender only the adjective stem is used (e.g., *rode bank,* red couch vs. *rood bed,* red bed). The syntactic processes in noun phrase production involve the retrieval of the grammatical gender of the noun and, on the basis of this information, the determination of the corresponding def-

[4] The Dutch gender system is arbitrary in the sense that the grammatical gender of a noun is not determined by natural gender, and there are hardly any rules on the basis of which the gender of a noun can be determined.

inite article or adjectival inflection. In a recent series of picture-naming experiments, Schriefers (1993) investigated syntactic processing during the production of Dutch noun phrases. The results showed that a gender incongruency effect occurred for both definite-determiner noun phrases and for no-determiner noun phrases [see Van Berkum (1998) for similar findings]. Schriefers (1993) accounted for these results in terms of Roelofs' (1992) spreading activation model of lexical processing that was developed within Levelt's (1989, 1992) framework of speech production. (See Schriefers and Jeschenikak, this volume, for details.)

The findings by Schriefers (1993) make it plausible to assume that in noun phrase production the definite article and the inflectional suffix are retrieved during syntactic processing. We hypothesize that if lexical access proceeds from the lemma to the word-form level, information about the grammatical gender of a noun will be activated earlier in time than its phonological segments. If we extend this to the time course of syntactic and phonological processing in noun phrase production, we hypothesize that determining a noun's definite article or inflectional suffix precedes the retrieval of the word's phonological segments. To test this hypothesis we constructed an experimental task in which both syntactic and phonological processes were related to motor responses. We used a two-choice reaction go/no-go paradigm to distinguish between the moments in time at which information obtained during syntactic and phonological processing affected the preparation of a motor response.

EXPERIMENTAL PARADIGM

The main task was noun phrase production. Participants were presented with colored pictures and were instructed to name the pictures using a no-determiner noun phrase. That is, their naming response included a color adjective, the correct adjectival inflection, and the noun (for example, *rood bed,* red bed; or *rode tafel,* red table). On half of the trials a frame appeared around the picture at 150 ms after picture onset, indicating that a secondary task had to be performed before noun phrase production. The secondary task was the critical experimental task. It involved a syntactic–phonological classification task consisting of the conjunction of a go/no-go decision and a left- or right-hand response. The syntactic classification involved the determination of the definite article of the noun. Participants were asked to decide whether the picture represented a *de* or a *het* word. The phonological classification involved the categorization of the noun's initial phoneme. Participants were asked to decide whether the name of the picture started with, for example, a /b/ or an /s/. After the syntactic–phonological classification task had been carried out, participants named the picture using a no-determiner noun phrase.

In the first experiment we attempted to detect response preparation based on syntactic information alone. In this experiment, the syntactic classification determined the response side. For example, a right-hand response had to be made if the noun had the definite article *de,* and a left-hand response had to be made if the noun had the definite article *het.* The phonological classification determined whether the response should be executed or not. For example, a response had to be executed if the picture name, i.e., the noun, began with a /b/, but it had to be withheld if it began with an /s/.

The logic behind the paradigm is as follows. At the moment of the appearance of the task cue (150 ms after picture onset), participants are in an early phase of noun phrase production. Since the main task is noun phrase production, on each trial the speech production process will be initiated directly after picture onset. The assumption underlying the syntactic–phonological classification task is that the critical information becomes available via the speech production process. That is, the retrieval of the noun's definite article follows the same processing route as the retrieval of the adjectival inflection, and therefore the noun's definite article becomes available during grammatical encoding. To retrieve the word's initial phoneme, the individual segments of a word have to be spelled out, and therefore a word's initial phoneme becomes available during phonological encoding (see, for example, Van Turennout *et al.,* 1997; Wheeldon & Levelt, 1995). If grammatical encoding precedes phonological encoding in time, then information about the noun's definite article should be available earlier in time than information about the word's initial phoneme. The critical test of this hypothesis involves the presence or absence of response activation on trials in which the phonological information instructs not to respond. From the LRP studies described earlier (e.g., Coles, 1989; Miller & Hackley, 1992; Smid *et al.,* 1992; Osman *et al.,* 1992; Van Turennout *et al.,* 1997), we know that information can be transmitted to the response system as soon as it becomes available. Moreover, these studies showed that the LRP can be used as a continuous measure of response preparation and that the LRP is sensitive to low levels of response activation that do not result in an overt response. Therefore, if a noun's definite article is available earlier in time than its initial phoneme, we expect to observe an LRP on both go and no-go trials. After some time, the retrieval of the word's initial phoneme will decrease response preparation on no-go trials, and the LRP will return to the baseline. On go trials, response preparation will continue, resulting in an overt response.

A second experiment was carried out to validate the results of the first experiment. From studies that were mentioned earlier, it is known that subjects are able to strategically control the use of partial information. To test whether strategic effects played a major role in the first experiment, in the second experiment the task instruction was reversed. Here, the syntactic classification determined whether or not to respond, and the phonological classification determined which hand to use. For example, in the case of a *de* word, a right-hand response had to be made for a word-initial /b/, and a left-hand response for a word-initial /s/. In the case of a *het* word, no response had to be given. Thus, in this experiment, a response could only be activated once the word-initial phoneme was available. The decision whether or not to respond could be made as soon as the gender information was available. Following the same logic as in experiment 1, we expect that if gender information is available earlier in time than phonological information, the go/no-go decision can be made before information about the response hand becomes available. Therefore, the presence of an LRP is only expected for go trials.

In addition to the LRP measurements, for each of the go and no-go conditions, average waveforms were computed for the midline frontal (Fz), central (Cz), and parietal (Pz) electrode sites. The results of these midline recordings do not bear directly on the experimental questions, but serve as an indirect validation of the materials used in the experiments, and as an indication of the reliability of the LRP recordings. Because the results from the midline recordings were as expected in both experiments, they will not be presented.

EXPERIMENT 1

Method

Participants

Sixteen undergraduate students (seven men) between 21 and 29 years of age from the participant pool of the Max Planck Institute for Psycholinguistics took part in the experiment. They were all native speakers of Dutch and had normal or corrected-to-normal vision. All participants were right-handed according to their response on an abridged and adapted Dutch version of the Oldfield Handedness Inventory (Oldfield, 1971). Familial left-handedness was reported by five of the participants. None of the participants had any neurological impairment or had experienced any neurological trauma according to their response on a questionnaire. They were paid for their participation.

Materials

The materials consisted of 48 colored line drawings with morphologically simple names. Half of the picture names were *de* words, which were the experimental items. They were all high frequency words (their mean token frequency was 2700 in 42 million words). The words consisted of one or two syllables and had an average length of 4.3 segments. The other 24 pictures were *het* words and were used as filler items. The decision to use only *de* words as experimental items was made in order to reduce the between-item variability in the experiments. The *het* words were matched to the *de* words for word frequency, number of syllables, and word length. There were no clear semantic differences between the set of *de* and *het* words. The experimental pictures were selected according to the following criteria: (1) Pictures had to be unambiguous. That is, a picture had to elicit a consistent naming response among subjects. To establish this, a pretest was run in which ten undergraduate students were asked to name 122 pictures. The pictures were successively presented for 600 ms on a NEC/Multisync 3D computer screen, with an interstimulus interval of 3 s. A picture was said to be unambiguous if it was given an identical name by at least nine of the ten participants. (2) The grammatical gender of the picture names had to be clear and relatively fast to retrieve. To determine the accuracy and speed of gender decisions, another pretest was run. The same 122 pictures that were used in the naming pretest were presented to ten undergraduates. Pictures were presented in the same way as was done in the naming pretest. Participants were instructed to indicate as quickly as possible whether the name of the picture was a *de* or *het* word by pressing either the left or the right button of a button box. Response latencies were measured from picture onset. Median reaction times and errors were calculated for the 122 pictures. To be selected, a picture had to be classified correctly by all participants and the median reaction time had to be less than 850 ms. The set of experimental pictures is listed in Appendix A.

The names of the pictures included four different word-initial phonemes, namely /b/, /s/, /v/, and /k/. Each of these word-initial phonemes was represented equally often in the picture set. The combination of the two syntactic categories and the four phonological categories resulted in four sets of experimental pictures: *de* word-initial /b/ [e.g., bloem (flower)], *de* word-initial /s/ [e.g., schoen (shoe)], *de* word-initial /v/ [e.g., voet (foot)], *de* word-initial /k/ [e.g., kast (cupboard)], and four sets of filler pictures: *het* word-initial /b/ [e.g., brood (bread)], *het* word-initial /s/ [e.g., schaap (sheep)], het word-initial /v/ [e.g., vuur (fire)], *het* word-initial /k/ [e.g., kasteel (castle)]. These materials were divided into two series. One series contained all word-initial /b/ and word-initial /s/ items, the other series contained all word-initial /v/ and word-initial /k/ items. The order in which the two series were presented was balanced across participants. The assignment of the four response types (left-hand go, right-hand go, left-hand no-go, right-hand no-go) to the separate picture sets was rotated across participants in such a way that each picture contributed equally to each of the responses. This was done to control for material-specific effects in the separate conditions. Examples of the stimuli are shown in Fig. 1. In this figure, a *de* word cues a left-hand response, and a *het* word cues a right-hand response. The response has to be executed if the picture name starts with a /b/ (go trials), and it has to be withheld if the picture name starts with an /s/ (no-go trials). To be able to derive LRPs for each individual subject by averaging over *de* words only, *de* words were assigned to the right hand in one series, and to the left hand in the other series. The order in which these assignments were given was balanced across subjects.

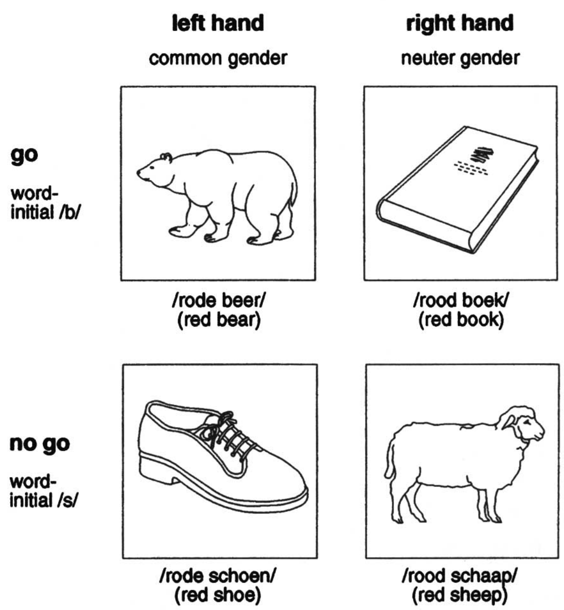

Fig. 1. Examples of the pictures used in the syntactic–phonological categorization task in experiment 1. In the figure, the Dutch picture names are shown below the pictures. In the experiment, pictures were presented in color, and naming responses included the color adjective, the correct adjectival inflection, and the picture name. The four pictures depicted here represent separate trials for the four experimental conditions. In this figure, a *de* word cues a left-hand response, and a *het* word cues a right-hand response. The response is executed if the picture name starts with a /b/ (go trials), and it is withheld if the picture name starts with an /s/ (no-go trials).

In addition to the pictures used in the judgment trials, 24 pictures were included that were used for filler-naming trials, in which subjects only named the pictures. Half of these fillers were *de* words and the other half were *het* words. Their word-initial phonemes differed from the word-initial phonemes of the targets. A set of practice items also was included. This set consisted of ten pictures representing a *de* word and ten pictures representing a *het* word. Half of the picture names started with a /p/, the other half started with an /h/.

Procedure

Participants were tested individually in a dimly lit sound-attenuating booth. They were seated in a comfortable chair in front of a high-resolution NEC/Multisync 3D computer screen. A trial started with the presentation of a fixation cross in the middle of the screen for 750 ms. The screen turned blank for 750 ms and then a picture was presented for 2500 ms. Participants were asked not to blink or to move their eyes during the period that the picture was on the screen. The pictures were presented in either the color yellow or red. Subjects were instructed to name the colored picture as quickly as possible using a no-determiner noun phrase. Naming latencies were measured from picture onset by a voicekey. The naming responses were recorded by a Sony 300 ES DAT recorder. On half of the trials a frame appeared around the picture at 150 ms after picture onset. The appearance of the frame signaled that the judgment task had to be carried out before picture naming. Push-buttons were attached to the left and the right arm of the chair. For go trials, participants made a hand response by pressing with their index finger either the button on the left side or the button on the right side of the chair. Push-button latencies were measured from frame onset. For no-go trials participants did not press any of the buttons. The frame remained on the screen for 1500 ms. Participants were instructed not to speak during this period. After the frame had disappeared participants named the picture. The presentation of the stimuli and the acquisition of the reaction time data were controlled by NESU, a system developed at the Max Planck Institute for Psycholinguistics, using a Hermac AT computer.

A session started with training on the task, using the set of practice pictures. Practice trials were presented until the participants performed the task accurately. After the training, electrodes for measuring electrophysiological activity were applied. The actual experiment consisted of two series of six blocks. In one series the /b/ and /s/ items were presented, and in the other series the /v/ and /k/ items were presented. The order in which the series were presented was balanced across subjects. Each of the series started with a block in which subjects were familiarized with the pictures and their names. The second block was a practice block containing all pictures that would be presented during that series. After the practice block, four experimental blocks were presented. An experimental block was composed as follows. The 12 experimental *de* word pictures and the 12 filler *het* word pictures were presented twice in a judgment trial, and once in naming-only trials. The filler-naming pictures were presented twice in naming-only trials. As a result, in each of the experimental blocks there were 48 naming-only trials and 48 trials that, in addition, had the critical judgment task. In half of the trials a picture was presented in red, in the other half a picture was presented in yellow. The items were presented in pseudorandomized order. Repeated items were always separated by at least eight other items, there were never more than two successive trials in the same condition, and there were never more than three successive naming-only trials or more than three successive judgment trials. Each block lasted 8 min, with a short break between the blocks. Between the first series and the second series participants were given a 10- to 15-min break. In the second series, the assignment of *de* and *het* words to either a left- or right-hand response was reversed. At the beginning of the second series, participants got an additional training session using the set of practice pictures to familiarize them with the new instruction.

Electrophysiological Recordings

The EEG was recorded from electrodes placed at midline frontal (Fz), central (Cz), and parietal (Pz) sites according to the International 10–20 system (Jasper, 1958), each referred to the left mastoid, and from C3′ and C4′ (approximately 3.5 cm lateral and 1 cm anterior to Cz). The difference in activity between C3′ and C4′ was recorded via a bipolar montage of the two electrodes. LRPs were derived according to the following formula:[5]

$$\text{LRP} = \text{right-hand } [C3' - C4'] - \text{left-hand } [C3' - C4']$$

Vertical and horizontal eye movements were monitored via a sub- to supraorbital bipolar montage, and a right to left canthal bipolar montage, respectively. A ground electrode was placed on the forehead, 10% from the nasion–inion distance above the nasion. Recordings of the EMG were made by placing pairs of electrodes above the M. flexor digitorum superficialis and the M. flexor digitorum profundus of each arm. For all recordings, Beckmann biopotential Ag–AgCl electrodes were used. Electrode impedance was kept below 5 kOhm for the EEG recording, and below 10 kOhm for the EOG and EMG recording. The EEG, EOG, and EMG signals were amplified by Nihon Kohden AB-601G bioelectric amplifiers and filtered

[5] This derivation of the LRP is equivalent to that of Coles (1989) and Gratton *et al.* (1992) [left hand (C4′ – C3′ + right hand (C3′ – C4′)/2], except that it has twice the amplitude.

with a high-frequency cutoff point of 30 Hz for the EEG and EOG, and a high-frequency cutoff point of 100 Hz for the EMG. A time constant of 8 s was used. The signals were digitized on-line with a sampling frequency of 200 Hz. Sampling started 200 ms before picture onset, with a total sampling epoch of 2700 ms. The EMG signal was rectified off-line.

Data Analysis

Data from critical trials were analyzed as described below. Filler trials were not further analysed.

Overt Responses. Trials on which participants produced other utterances than the expected ones, started speaking while the frame was still on the screen, gave an incorrect hand response, or did not respond on go trials within 2000 msec after frame onset, were eliminated from the data set. Moreover, each trial was visually inspected for the occurrence of EMG activity. All go trials in which EMG activity was detected on the incorrect response side were excluded from further analyses, as were all no-go trials in which EMG activity occurred. This was done to make sure that the development of the LRP on go trials would not be biased by trials in which both response hands were activated and to avoid the possibility that the presence of an LRP on no-go trials could be attributed to incomplete or incorrect go/no-go analyses.

Event-Related Potentials. All single trial waveforms containing eye movement artifacts, amplifier blocking, or electrode drifting, in the time window of 200 ms before picture onset to 1500 ms after picture onset, were removed from the data set. Per subject, the minimum number of trials left for averaging was 35 per condition. From each single trial waveform, the average voltage in the 200-ms period preceding picture onset was subtracted.

LRPs were derived separately for the go and no-go conditions. To test for the presence of an LRP and to estimate its onset, analyses were performed on 50 ms intervals, starting from frame onset in sequential steps of 10 ms (e.g., 150–200 ms, 160–210 ms etc.). For each window a one-tailed t test with a 95% confidence interval was performed to test whether the mean voltage within the window exceeded the mean voltage within the baseline interval. An LRP was defined to be present if five or more consecutive windows resulted in a significant t value. The onset of the first of these consecutively significant windows determines the LRP onset latency.

To determine the point of divergence between the go and no-go LRPs, the average voltage at each individual time point of the no-go waveform was subtracted from the average voltage at the corresponding time points of the go waveform. One-tailed t tests were performed to test whether the mean go/no-go difference scores differed significantly from zero, using the same procedure as described for the individual LRP waveforms. The point of divergence was defined as the beginning of the earliest of five or more consecutive time-windows that resulted in significant t-values.

Results

Overt Responses

The mean push-button latency, measured from frame onset, for the correct go trials was 822 ms [standard deviation (SD) = 264]. The mean error rate for the go trials was 4.8% (on 1.3% of the go trials an incorrect response was given, on 2.5% of the go trials EMG activity occurred on both response sides). For the no-go trials the mean error rate was 1.5%. Because the error rates were low, they were not further analyzed. The mean noun phrase production latency, measured from picture onset, for the naming-only trials was 894 ms ($SD = 168$).

Lateralized Readiness Potentials

In total, 18% of the trials were rejected due to errors and EEG artifacts. The rejected trials were equally distributed across participants and conditions. Per condition, the minimum number of trials left for averaging was 35 for each participant.

The grand average LRP waveforms for the go trials and the no-go trials are presented in Fig. 2. As this figure shows, a negative LRP developed on both the go trials *and* the no-go trials. That is, on both go and no-go trials, a lateralization of the readiness potential was observed, indicating the presence of response preparation for the cued response hand. On go trials the LRP started to deviate significantly from zero at 390 ms after picture onset [$t(15) = -1.90$, $SD = 1.184$, $p = 0.05$]. On no-go trials the LRP became significant at 370 ms after picture onset [$t(15) = -1.90$, $SD = 0.710$, $p = 0.05$]. Initially, the no-go LRP developed at the same rate as the go LRP. However, at 410 ms after picture onset, the two waveforms started to diverge [$t(15) = -1.78$, $SD = 1.161$, $p = 0.05$]. While the go LRP kept on developing, reaching its maximum value around 760 ms after picture onset, the no-go LRP slowly returned to the baseline. From 620 ms after picture onset, the no-go LRP no longer differed significantly from zero [$t(15) = -1.438$, $SD = 0.710$, $p > 0.05$].

Discussion

The main finding of experiment 1 concerns the presence of an LRP on no-go trials. We found that at 370 ms after picture onset, an LRP started to develop on no-go trials, in the absence of concomitant EMG activity. This observation of an LRP on trials in which participants refrained from respond-

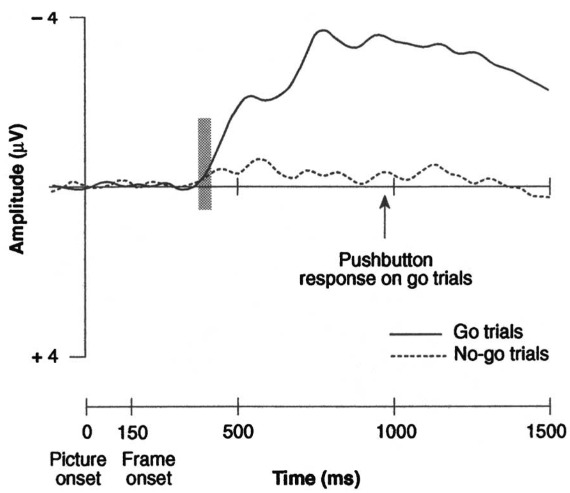

Fig. 2. Grand average (N = 16 participants) lateralized readiness potentials on go trials and no-go trials in experiment 1. The grammatical gender decision determined response hand; the word-initial phoneme decision determined whether a trial was a go or a no-go trial. Significant lateralization of the readiness potential was obtained both on go and on no-go trials. The shaded area shows the time interval in which the go and the no-go LRPs were significantly different from the baseline, but not from each other.

ing implies that the response hand was selected earlier in time than the go/no-go decision was made. In the present experiment, response selection was based on the definite article of the noun. Therefore, the results indicate that at 370 ms after picture onset gender information was sufficiently available to preliminarily activate a lateral response. The go and the no-go LRP initially developed at the same rate, but at 410 ms after picture onset the two waveforms started to diverge. On go trials the LRP kept on developing, but on no-go trials the LRP returned to the baseline without any EMG activity being produced. Since the go/no-go distinction was based on the word's initial phoneme, the go/no-go divergence point provides information about when phonological information started to influence motor processes. We found that at 410 ms after picture onset a sufficient amount of phonological information of the word was available to either decrease (on no-go trials) or further develop (on go trials) response preparation.

It is tempting to conclude from these findings that during noun phrase production gender information is retrieved earlier than phonological information. However, before we can attribute these findings to differences in the time course of grammatical and phonological processing, we need to rule out an alternative explanation for the obtained pattern of results.

This alternative explanation concerns the possibility that individuals can have strategic control over the temporal order in which distinct types of information are used for response preparation. Gratton *et al.* (1992) provided data that suggested that in a visual attention task participants can modulate the use of partial information. They showed that the influence of partial information on response preparation was dependent on its usefulness for giving fast and correct responses. Moreover, a study by Smid *et al.* (1992) showed that participants can control which of two visual stimulus attributes is made available for response preparation first. Smid *et al.* (1992) observed that in a two-choice go/no-go task, subjects were able to use either one of two separate stimulus attributes for early response preparation, depending on which of the attributes determined response hands. The importance of these findings for the present study concerns the possibility that information is available, but not used for response preparation. This could mean that the initial response preparation we observed on no-go trials might have resulted from a strategy to always first use the gender information to select response hands and to then use the phonological information to complete the go/no-go decision. Thus, a noun's syntactic and phonological properties might have been activated in parallel during the speech production process, but due to strategic control of the available information, these properties were used for response preparation at different moments in time. Experiment 2 was designed to exclude this possible explanation of the results. In this experiment we reversed the assignment of the syntactic and phonological evaluation to the left-right and go/no-go dimensions. The reversal allows us to determine whether the response preparation observed on no-go trials can be attributed to early availability of gender information, or just to strategic use of this information.

EXPERIMENT 2

In experiment 2 the same experimental paradigm was used as in the first experiment. Participants were presented with colored pictures and were instructed to name the picture as quickly as possible using a no-determiner noun phrase. On half of the trials a frame appeared around the picture at 150 ms after picture onset. The frame served as a cue to perform the syntactic/phonological decision task. In experiment 2 the assignment of the syntactic and phonological decision to the left-right and go/no-go dimensions was the reverse of the one used in experiment 1. The word-initial phoneme decision determined with which hand to respond, and the gender decision determined whether or not to execute the response. This task configuration emphasizes the early use of phonological information: previous LRP studies have shown that in a choice reaction go/no-go task, subjects assign priority to the extraction of information that can be used to select a response hand (Coles *et al.*, 1995), which in experiment 2 is the phonological information. Nevertheless, if during noun phrase production syntactic processing precedes phonological processing, then an LRP should develop only on go trials, and not on no-go trials.

Method

Participants

Sixteen undergraduate students (four men) between 19 and 29 years of age from the participant pool of the Max Planck Institute for Psycholinguistics were paid for their participation in the experiment. Eight of them had already participated in experiment 1. All participants were native speakers of Dutch and had normal or corrected-to-normal vision. They were all right-handed according to their response on an abridged and adapted Dutch version of the Oldfield Handedness Inventory (Oldfield, 1971). Familial left-handedness was reported by four of the participants. None of the participants had any neurological impairment or had experienced any neurological trauma according to their response on a questionnaire.

Procedure

As in the first experiment, the participants were presented with two series of six blocks. In one of the series *de* words instructed to execute the response (go trials), in the other series *de* words instructed not to respond (no-go trials). The assignment of *de* and *het* words to either a go or a no-go response was reversed between the series, to be able to derive both go and no-go LRPs for each of the participants averaging over *de* words only. At the beginning of the second series, the participants were familiarized with the new instruction during a short training session. The order in which the assignments were given was balanced over subjects. The rest of the procedure was the same as described for experiment 1.

Materials, apparatus, electrophysiological recordings, and data analysis were the same as described for experiment 1.

Results

Overt Responses

The mean response time for the correct go trials was 717 ms (SD = 261.82), measured from frame onset. The mean error rate for the go trials was 4.9% (on 1.6% of the go trials an incorrect response was given and on 0.7% of the trials no response was given, on 2.6% of the go trials EMG activity occurred for both response sides). For the no-go trials the mean error rate was 3.1%. Because error rates were small, they were not further analyzed. The mean noun phrase production latency for the naming-only trials, measured from picture onset, was 828 ms (SD = 162).

Lateralized Readiness Potentials

In total, 18% of the trials were rejected due to errors and EEG artifacts. The rejected trials were equally distributed across participants and conditions. Per condition, the minimum number of trials left for averaging was 35 for each participant.

The grand average LRP waveforms for go trials and no-go trials are presented in Fig. 3. In this figure, we can see a negative LRP developing on go trials. The LRP started to deviate from zero at 380 ms after picture onset [$t(15) = -2.42$, $SD = 1.05$, $p = 0.03$] and reached its maximum around 615 ms after picture onset. On no-go trials, no development of an LRP was observed [$t(15) = 0.36$, $SD = 1.03$, $p = 0.72$]. The no-go waveform did not significantly deviate from zero during the epoch, indicating that no response preparation occurred on no-go trials.

In addition to the overall analyses, separate analyses were performed on the LRP data of the eight subjects who participated both in experiment 1 and experiment 2. These analyses showed that for these eight participants an LRP was obtained on go and no-go trials in experiment 1. The no-go LRP started to significantly deviate from zero at 360 ms after picture onset [$t(7) = -1.90$, $SD = 0.78$, $p = 0.05$], and the go LRP reached significance at 400 ms after picture onset [$t(7) = -2.87$, $SD = 0.72$, $p = 0.03$].[6] In experiment 2, a significant LRP started to develop on go trials at 380 ms after picture onset [($t(7) = -2.06$, $SD = 1.12$, $p = 0.05$)]. However, no significant LRP was observed on no-go trials for these participants.

Discussion

The results of experiment 2 showed that whereas on go trials an LRP started to develop at 380 ms after picture onset, no development of an LRP was observed on no-go trials. The absence of an LRP on no-go trials indicates that on these trials phonological information did not affect response

[6] In addition, analyses were performed on the data from the eight participants who only participated in experiment 1. These analyses showed that also for this group participants a significant no-go LRP was obtained, starting at 410 ms after picture onset [($t(7) = -2.18$, SD = 0.68, p = .05).

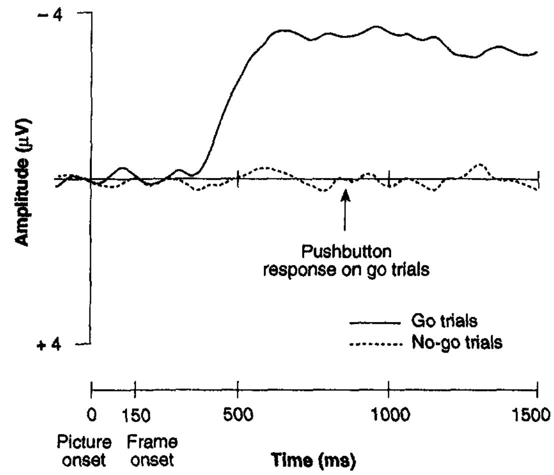

Fig. 3. Grand average (N = 16 participants) lateralized readiness potentials on go and no-go trials of experiment 2. The grammatical gender decision determined whether a trial was a go or a no-go trial; the word-initial phoneme decision determined the response hand. No significant lateralization of the readiness potential was obtained on no-go trials.

preparation. Gender information was already available to make the go/no-go distinction before phonological information could be used to select response hands.

The results of experiment 2 rule out the possibility that the no-go LRP observed in experiment 1 was due to a selective use of information. If the no-go LRP had resulted from the strategy to always select response hands first, an LRP should have developed on no-go trials independent of whether response hand was determined by syntactic or phonological information. This is not what we observed. In experiment 2 we found that phonological information did *not* serve as partial information to selectively activate response hands before the syntactically based go/no-go distinction had been made. However, since different subjects participated in the two experiments, the absence of a no-go LRP in experiment 2 might reflect that subjects in experiment 1 used a response selection strategy, whereas subjects in experiment 2 did not. Analyses of the data from the eight subjects who participated in both experiments show that for this group of subjects a no-go LRP was obtained in the first, but not in the second experiment. This rules out that the disappearance of the no-go LRP in experiment 2 was due to a difference in the use of strategies between participants.

The overall response latency in experiment 2 was faster than in experiment 1. The reason for this is unclear. However, the difference in mean response latencies between the experiments has no implications for our interpretation of the no-go LRP obtained in experiment 1. As we mentioned earlier, evidence has been provided that shows that the use of partial information to select response hand leads to a reduction in reaction time and error rate (e.g., Gratton *et al.,* 1992; Smid *et al.,* 1992). We found that the mean RT in experiment 1 was *slower* than the mean RT in experiment 2. Under a strategy, account of the present LRP results, RTs in experiment 1 should have been faster than RTs in experiment 2.

GENERAL DISCUSSION

In the present study we aimed to find evidence on the time course of grammatical and phonological processing during speech production. We showed that the LRP is differentially sensitive to the moments in time at which syntactic and phonological information become available during noun phrase production.

In experiment 1, we found that initially an LRP developed on both go and no-go trials, indicating that syntactic information was used to select response hand before phonological information was used to make the go/no-go distinction. In experiment 2, the phonologically based response hand decision only resulted in an LRP on trials in which syntactic information cued a response. The findings support the claim that syntactic information influences response preparation at an earlier moment in time than phonological information.

The LRP's sensitivity to the moments at which syntactic and phonological properties of a word become available is also illustrated by the following. We derived the go/no-go difference waveform for experiment 1. This difference waveform is obtained by subtracting the LRP on no-go trials from the LRP observed on go trials. The onset of this waveform represents the moment at which phonological information affected the LRP. We compared the onset of the go/no-go difference waveform with the LRP onsets obtained on the go trials in experiment 1 and in experiment 2. In experiment 1, the onset of the LRP depended on the influence of syntactic information, whereas in experiment 2 it depended on when phonological information affected the LRP. To reduce the variability in LRP onsets due to subject-related reaction time differences between the experiments, for each experiment we selected eight participants whose mean reaction times were between 600 and 800 ms (the mean response latency for the two groups was 733 ms for experiment 1, and 712 ms for experiment 2). Figure 4a presents the go/no-go difference waveform for this subject group in experiment 1 together with the corresponding go LRP (upper panel). In Figure 4b the same

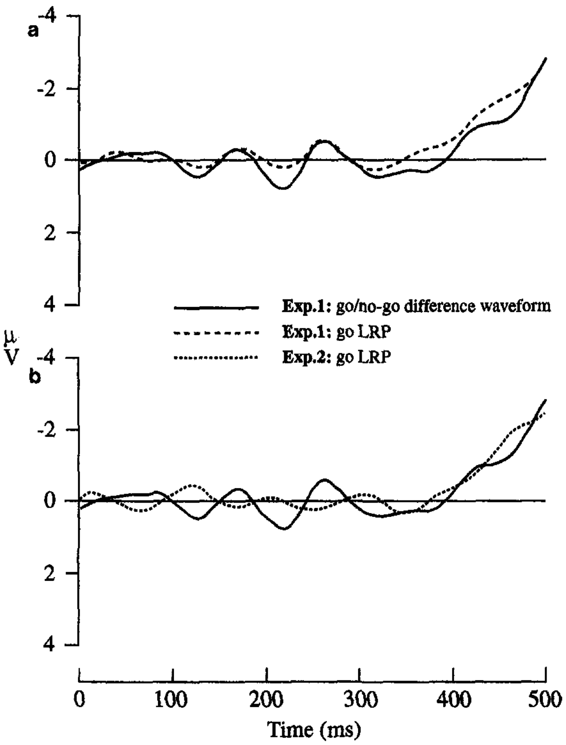

Fig. 4. **a:** Grand average LRP on go trials and the go/no-go difference waveform for eight participants in experiment 1 whose mean reaction times were between 600 and 800 ms. Visual inspection of the waveforms shows that the go LRP started to develop earlier in time than the go/no-go difference waveform. **b:** Grand average LRP on go trials for eight participants in experiment 2 whose mean reaction times were between 600 and 800 ms, together with the go/no-go difference waveform for the selected participants in experiment 1. Visual inspection of the waveforms shows that the go LRP in experiment 2 started to develop at about the same moment in time as the go/no-go difference waveform in experiment 1.

go/no-go difference waveform is shown together with the go LRP for the selected subjects in experiment 2.

As can be seen in these figures, the go LRP in experiment 1 started to develop earlier in time than the go/no-go difference waveform, indicating that syntactic information affected response preparation earlier in time than pho-nological information. When we compare the go/no-go difference waveform with the go LRP obtained in experiment 2 (Figure 4b), no such difference appears. The similar onset latencies of the go/no-go difference waveform in experiment 1 and the go LRP in experiment 2 suggest that in both experiments phonological information started to influence the motor processes around the same moment in time, independent of whether this information determined response hand or the go/no-go distinction.

Together, these results indicate that in the present study the LRP is indeed sensitive to the moments at which the separate types of information are made available to the response system and that the LRP is not reflecting effects of specific task configurations. Under the plausible assumption that the definite article and the word-initial phoneme become available for response preparation during the speech production process, we can conclude that the LRP paradigm provides insight into the time course of grammatical and phonological processing in noun phrase production. We can now turn to the implications of the results for the temporal parameters of grammatical and phonological encoding.

Time Course of Grammatical and Phonological Processing

In noun phrase production, the closed-class elements (i.e., the definite article, the adjectival inflection) are retrieved during the stage of grammatical encoding (e.g., Bock & Levelt, 1994; Dell, 1986, 1990; Kempen & Hoenkamp, 1987; Levelt, 1989; Schriefers, 1993). The noun lemma activates its grammatical gender and, on the basis of this gender information, the correct definite article can be retrieved. In experiment 1, the onset of the LRP was determined by the noun's definite determiner. Since grammatical encoding is required to retrieve this information, the development of an LRP around 370 ms reveals that by then grammatical processing was well under way. The observation that for a short period of time the LRP developed at the same rate on both go and no-go trials, indicates that at the same moment, the word-initial phoneme was not yet available. From studies on the time course of phonological encoding we know that a word form is constructed from left to right (e.g., Meyer, 1990; Meyer & Schriefers, 1991; Van Turennout *et al.*, 1997; Wheeldon & Levelt, 1995). This implies that a word's initial phoneme is retrieved relatively early during phonological encoding. Therefore we conclude that the late effect of word onset information on response preparation, compared to gender information, provides clear evidence for the idea that in speech production grammatical processing precedes phonological processing in time.

The data support hierarchical theories of sentence production in which lemmas are retrieved and a syntactic frame of the speech fragment is built-up at the grammatical processing level, before, at the phonological processing level, the sound pattern of the fragment is constructed. Since we focused on the phonological encoding of the noun, we cannot, on the basis of these data, claim that during noun phrase production syntactic processing has to be completed before phonological encoding can start. Although the noun's gender was required to retrieve the adjectival inflection and to fully encode the word form, it could well have been the case that phonological encoding of the adjective already started before each slot in the syntactic frame had been filled (cf. Schriefers 1992, 1993). An important and still open question for research on the discreteness of grammatical and phonological encoding concerns the size of the processing units at each of these levels in various kinds of utterances.

Time Course of Lexical Retrieval

As was mentioned above, according to most theories of lexical retrieval, the syntactic properties of a lexical item are carried by the lemma (e.g., Bock, 1982; Dell, 1986; Garrett, 1976; Kempen & Huijbers, 1983; Levelt, 1989; Roelofs, 1992). The present study examined the relation in time between grammatical gender retrieval and word-form retrieval. Since the selection of the correct gender information requires that the lemma has been retrieved, the data enable us to speculate about how lemma selection and phonological encoding relate to each other in time. We have to be careful in using either the LRP onset or the onset of the go/no-go difference waveform as a quantitative estimate of the moment in time at which information becomes available during noun phrase production. The onset of these waveforms not only depends on the retrieval of information, but also on when this information is used for response preparation. Therefore, on their own, these values do not provide an exact estimation of when information is retrieved. However, the time interval *between* the LRP onset and the onset of the go/no-go difference waveform can be used as an estimate of the length of the period during which lemma information, but *not* phonological information, influenced response preparation. In experiment 1, we found that the no-go LRP started to develop at 370 ms after picture onset and developed simultaneously with the go LRP until 410 ms after picture onset. At 410 ms after picture onset, the no-go LRP gradually returned to the baseline, while the go LRP continued to develop. This means that while at 370 ms after picture onset syntactic information was available to select response hand, an additional 40 ms was required for phonological information to become available to make the go/nogo distinction. On the basis of these data, we conclude that a noun's lemma is selected before its phonological form, but that the primacy of syntax over phonology lasts, in this case, for only some 40 ms.

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APPENDIX A

Dutch names and their English translations for the target pictures in experiment 1 and experiment 2, and their median naming latencies and gender decision latencies as obtained in the pretests:

Picture names grouped by word-initial phoneme	Reaction time (ms)	
	Naming	Gender decision
/b/		
bank [couch]	665	762
bloem [flower]	660	747
boom [tree]	623	776
bril [glasses]	742	700
broek [trousers]	682	769
baby [baby]	848	801
/s/		
schoen [shoe]	642	688
spin [spider]	618	680
ster [star]	639	886
stoel [chair]	608	686
sleutel [key]	669	701
spijker [nail]	734	706
/v/		
vaas [vase]	801	693
vis [fish]	673	659
vlag [flag]	696	754
voet [foot]	698	782
vinger [finger]	767	684
vlinder [butterfly]	642	672
/k/		
kaars [candle]	570	793
klok [clock]	825	784
knoop [button]	789	766
kast [cupboard]	752	843
kikker [frog]	642	797
koffer [suitcase]	725	740