

59 The Neural Correlates of Language Production

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ABSTRACT This chapter reviews the findings of 58 word production experiments using different tasks and neuroimaging techniques. The reported cerebral activation sites are coded in a common anatomic reference system. Based on a functional model of language production, the different word production tasks are analyzed in terms of their processing components. This approach allows a distinction between the core process of word production and preceding task-specific processes (lead-in processes) such as visual or auditory stimulus recognition. The core process of word production is subserved by a left-lateralized perisylvian/thalamic language production network. Within this network there seems to be functional specialization for the processing stages of word production. In addition, this chapter includes a discussion of the available evidence on syntactic production, self-monitoring, and the time course of word production.

In reading the neuroscience literature on language production, one might infer that producing language simply means producing words. Neuroimaging studies of language production typically require subjects to generate (silently) words in response to other words (as in verb generation)—words of a particular semantic category, names of depicted objects, words beginning with a particular phoneme (or letter), and the like. Such studies have provided a wealth of information on the neurophysiology of lexical access, but they should not obscure our perspective on the larger speech production process. Speaking is, after all, our most complex cognitive-motor skill, designed by evolution to support communication in large clans of *homo sapiens*. A vast network of brain structures, both cortical and subcortical, contributes to the high-speed generation of utterances in never-identical communicative settings. It also generates the ever-babbling internal speech, speech whose representational functions are still fallow research territory.

In this chapter, therefore, we begin with a summary outline of the functional organization of speaking, laying out the processing components involved, including grammatical encoding, phonological encoding, and self-monitoring. These components then offer a structure for

the subsequent review of neuroimaging studies, most of them word production studies.

The functional organization of language production

The interactive generation of utterances in conversation, the evolutionary basic setting for language use, involves a multicomponent processing system. It can map communicative intentions onto articulatory gestures, which in turn produce the auditory signals from which the interlocutor can derive or recognize these intentions. Figure 59.1 diagrams the major processing components involved (roughly as defined in Levelt, 1989). Although the modeling of component processes and their interaction still differs substantially among theories of language production (see, in particular, the BBS commentaries to Levelt, Roelofs, and Meyer, 1999), there is reasonable consensus about the major components involved in the generation of speech.

It makes both functional and neuropsychological sense to partition these components as follows. There is, on the one hand, a rhetorical/semantic/syntactic system. It decides on the communicatively effective information to express, puts it in terms of linguistically expressible conceptual structures (“messages”), whereupon these messages trigger the generation of ordered lexicosyntactic structures (“surface structures”). On the other hand, there is also a phonological/phonetic system whose aim it is to generate the appropriate articulatory shape for these surface structures. Both systems have access to a huge mental lexicon. The rhetorical/semantic/syntactic system has, in addition, access to communicatively relevant perceptual and memory systems which represent the speaker’s external and internal world. The form-generating system has access to a mental syllabary. Let us now turn to the processing components in slightly more detail.

CONCEPTUAL PREPARATION In preparing a message for expression, we exercise our social and rhetorical competence. An effective utterance will mind the knowledge state of the listener, the intention to be realized, the

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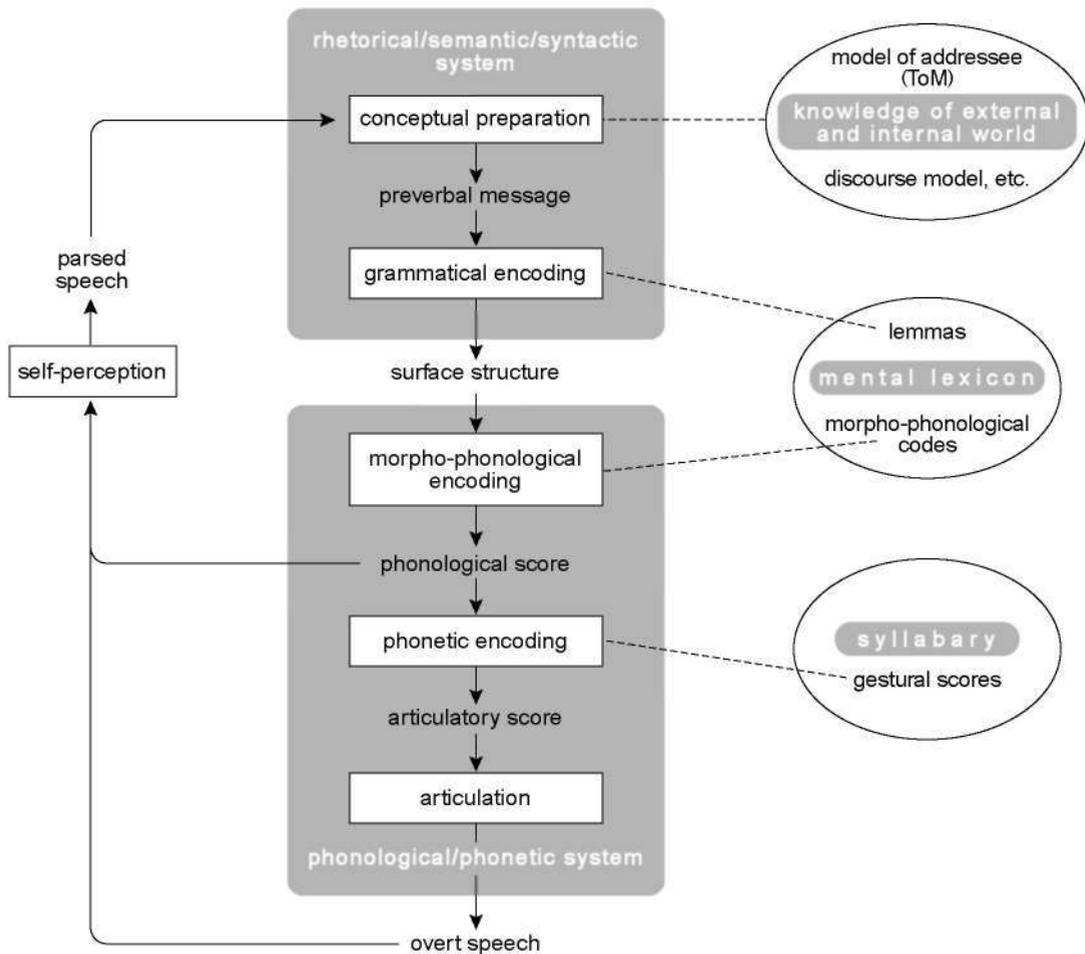


FIGURE 59.1 Framework of processing components involved in speech production. (From Levelt, 1999.)

achieved state of discourse, the attentional focus of the interlocutor, and so on (Clark, 1996). Conceptual preparation capitalizes on our “theory of mind” skills—the ability to estimate an interlocutor’s state of relevant beliefs and desires (Premack and Premack, 1995). All this is subsumed under *macroplanning* (Butterworth, 1980; Levelt, 1989). One important aspect of macroplanning is “linearization”—deciding what to say first, what to say next, etc. (Levelt, 1981). This involves both rhetorical decisions about how to guide the listener’s attention and efficient management of working memory.

There is, in addition, *microplanning*. To be expressible in language, a conceptual structure must be in a special, “propositional” format. Visual images, musical patterns, and motor images are typically in a different representational format. If they are to be expressed linguistically, they must be recoded. This recoding is flexible, and dependent on the communicative goals. The same visual image of a sheep and a goat juxtaposed can be expressed as “there is a sheep, and a goat to the right of it” or “there is a goat, and a sheep to the left of it” (and in

many other ways). This phenomenon, called *perspective taking*, is not limited to the recoding of visual representations (cf. Levelt, 1996; Clark, 1997). The terminal elements in the propositional format must be *lexical concepts*, concepts for which there are words in the language. The choice of lexical concept is an important aspect of perspective taking. There are always multiple ways to refer to the same entity: *The animal/dog/labrador frightened me* or *the interval/consonant/fifth is out of place here*. Perspective taking is ubiquitous in language production. As speakers, we are continuously mediating between visual, motor, person, etc., imagery systems and semantic systems of lexical concepts. This mediation is under the pressure of communicative effectiveness. It wouldn’t be surprising if conceptual preparation turns out to be a widely distributed cerebral affair.

GRAMMATICAL ENCODING The lexical concepts that are activated in constructing a message for expression trigger the retrieval of *lemmas* from the mental lexicon. These are syntactic words, characterized by a syntactic

frame. There is a lemma for each lexical concept and for all function words. Syntactic word frames specify, among other things, how semantic arguments in the message (such as theme or recipient) should be mapped onto syntactic functions (such as direct or indirect object). In *Sally gave Peter a bike*, the recipient of Sally's giving is Peter and the theme is a bike. The syntactic frame of *give* moves the corresponding lemmas into indirect and direct object position, respectively. The syntactic frames of selected lemmas (verbs, nouns, etc.) combine and recombine to build a syntactic pattern for the message as a whole, a "surface structure." Surface structures are *incrementally* created. As soon as a first lemma is selected, syntactic construction is initiated, and it keeps going as further lemmas become available. These processes are typically disturbed in agrammatic patients.

MORPHOPHONOLOGICAL ENCODING A first major step in the generation of the articulatory shape of an utterance involves the creation of phonological words and phrases and the generation of intonational phrases. A core process here is the retrieval of phonological codes. Once selected, a lemma activates the phonological codes of each of its morphemes. For instance, after selection of the noun lemma *postbox*, the codes for each of its morphemes *post* and *box* are activated: /pE*st/, /bAks/. Most neuroimaging work in word production involves monomorphemic words and hence reveals nothing about the production of complex morphology.

Accessing a word's or morpheme's phonological code is no trivial matter, neuropsychologically speaking. Anomic disorders, for instance, are often blockades of phonological access with preserved access to syntactic information. Badecker, Miozzo, and Zanuttini (1995), for instance, reported the case study of an Italian anomic patient who is unable to name any picture, but in all cases knows the gender of the target word. Gender is a syntactic word property, encoded in the lemma. Jescheniak and Levelt (1994) have shown that the "word-frequency effect" (i.e., picture naming is slower when the name is a low-frequency word than when it is a high-frequency word) emerges during the retrieval of a word's phonological code. It does not arise at the level of lemma selection. Clearly, there is a dedicated system involved in the storage and retrieval of phonological codes.

The primary use of phonological codes is the generation of syllabic structure. The domain of syllabification is the phonological word. Syllabification doesn't respect lexical boundaries. In the phrase *I understand it*, the syllabification becomes *I un-der-stan-dit*, where the last syllable (*dit*) straddles a lexical boundary; *understandit* is a single phonological word. Syllabification also depends on inflection—*un-der-stand*, *un-der-stands*, *un-der-*

stan-ding—it is a highly context-dependent process. Most probably, a word's syllabification is not stored in its phonological code. The incremental syllabification of phonological words in connected speech is an independent computational process (cf. Levelt, Roelofs, and Meyer, 1999, for a detailed theory of phonological word formation).

As the surface structure expands, the speaker also composes larger phonological units. One such unit is the *phonological phrase*. It is a metrical unit. It tends to start right after the lexical head of a surface phrase (i.e., right after the noun of a noun phrase, or right after the main verb in a verb phrase), and it leads up to include the next lexical head. Here is such a metrical grouping: *the fellow/that I sought/was standing/near the table/*. Within a phonological phrase, there is so-called nuclear stress on the lexical head word.

Phonological phrases combine into smaller or larger *intonational phrases*. These are sense units that are characterized by their intonation contour. The whole of the example sentence above can be cast as a single intonational phrase. Pitch movement will then lead up to the *nuclear tone*, which consists of a pitch accent on the first syllable of *table* (*ta-*), followed by a boundary tone on the last syllable of the phrase (*-ble*). Falling boundary tones suggest completion, whereas rising boundary tones invite continuation either on the part of the speaker or on the part of the interlocutor. The ultimate output of morphophonological encoding is called the *phonological score* (in analogy to a musical score).

PHONETIC ENCODING The incremental generation of metrically grouped and pitch-marked phonological syllables is closely followed by the generation of gestural patterns for these syllables in their larger context. It is largely unknown what kind of processing mechanism creates these gestural scores. The system must be generative in that speakers can produce syllables that they never produced before (in reading nonsense words for instance). Still, it appears from language statistics that speakers of English or Dutch do some 85% of their speaking with no more than 500 different syllables (out of more than 12,000 different syllables; cf. Schiller et al., 1996). In these languages, speakers hardly ever produce an entirely new syllable. Also, many languages (such as Mandarin Chinese) have no more than a few hundred different syllables. Hence, it is reasonable to assume that these highly overused articulatory routines are stored somewhere in the brain, and the premotor cortex is a good candidate (cf. Rizzolatti and Gentilucci, 1988). This repository of gestural scores is called the *mental syllabary* (Levelt, 1992). The generated gestural pattern for an utterance is called the *articulatory* or *gestural score*.

ARTICULATION Whatever the origin of the articulatory score, it is ultimately executed by the laryngeal and supralaryngeal systems. These are under the control of the larynx and face area of the somatosensory cortex, caudal midbrain structures, and cerebellum. Articulatory execution is quite flexible. The same articulatory target can often be realized in different ways. The system tends to minimize effort, given the prevailing physical contingencies. It is, for instance, possible to speak intelligibly with food or even a pipe in the mouth. Articulation is our most sophisticated motor system. It is normal to produce some 12 speech sounds (consonants, vowels) per second, and this involves control over some 100 different muscles. This masterpiece is achieved by concurrent, overlapping execution of articulatory gestures (Liberman, 1996).

SELF PERCEPTION, MONITORING, AND REPAIR Speakers are their own listeners. Whether listening to one's own speech or listening to somebody else's speech, the same superior temporal lobe structures are activated (McGuire, Silbersweig, and Frith, 1996, Price, Wise, et al., 1996). This feedback is one way for the speaker to exercise some degree of output control. For instance, we immediately adapt the loudness of our speech to the prevailing noise in our speech environment. We also tend to correct obvious or disturbing output errors or infelicities. This self-monitoring, however, is not based solely on the feedback of overt speech. We can also monitor our internal speech and catch an error before the word is (fully) pronounced (as in: *we can go straight to the ye-*, *to the orange node*, where the almost-error here is *yellow*). What is this internal speech? As Wheeldon and Levelt (1995) have experimentally argued, it's likely that what we monitor for in internal speech is the phonological score, i.e., the output of morphophonological encoding.

This bird's eye view of the speaker's functional organization provides us with the further layout of this chapter. We first discuss the many neuroimaging studies in word production. In that discussion, we are guided by a stage theory of word production, as diagrammed in figure 59.1. Following that, we turn to the few studies of grammatical encoding and to some studies of internal speech and self-monitoring.

Producing words: A task analysis

In neuroimaging studies of word production, we encounter a rich variety of tasks—verb generation, noun generation, picture naming, word reading, word repetition, generating words starting with a particular letter, and the like. The choice of experimental tasks and con-

trols demonstrates both inventiveness and ingenuity, but may also carry with it some degree of arbitrariness. Subtraction studies, in particular, are based on a difference logic that requires a componential analysis of the functional organization involved in the experimental and control tasks. It is rare, however, that such a componential analysis is independently performed and tested—say, by way of reaction time studies. Pending such task analyses, the present review can provide only a theoretical handle, presenting a componential analysis of normal word production based on the theoretical framework in figure 59.1. A fuller, comprehensive account of that functional word production theory can be found in Levelt, Roelofs, and Meyer (1999).

The left panel of figure 59.2 represents the components—the “core processes”—involved in word production, as derived from figure 59.1. As far as word production is concerned, the core aspect of conceptual preparation is to map some state of affairs onto a lexical concept. The state of affairs can be a perceptual image (as in picture naming), the image of an activity (as in verb generation), and so forth. In all cases we find perspective taking—a decision on the type of lexical concept that is apparently wanted in the experimental task. (For instance, one must decide whether to name an object by its basic level term, such as *dog* in normal picture naming, or to use a superordinate term, such as *animal* in a semantic categorization task.) The grammatical encoding aspect of word production is lemma access—selecting the appropriate syntactic word. It is at this step that the word's syntactic properties, such as gender, mass/count noun, syntactic argument structure, etc., become available. There are two major aspects to morphophonological encoding, now distinguished in figure 59.2. The first one, morphological encoding, provides access to the word's morphological structure and the phonological codes of each morpheme. For the monomorphemic words used in almost all neuroimaging studies, this stage is just accessing the word's phonological code. An important independent variable here, affecting just this stage, is word/morpheme frequency. The second one, phonological encoding proper, is the incremental construction of the phonological word and in particular the word's syllabification in context. This is probably the word representation figuring in internal speech. It may be (but need not be) the end stage in silent word generation tasks. The next component, phonetic encoding, provides a gestural or articulatory score for the word. It is likely that highly practiced syllabic motor routines are accessed at this stage. In the final stage of word production, the constructed or retrieved gestural score is executed by the articulatory apparatus, resulting in an overt acoustic signal, the spoken word. In all nonsilent word generation tasks

| Tasks | (silent) Picture naming | (silent) Verb or Noun generation | (silent) Reading | (silent) Pseudoword reading | (silent) Generation from initial letters | (delayed) Word repetition |
|--------------------------|---------------------------------|---|----------------------------|--|---|--|
| Lead-in Processes | visual object recognition | visual or auditory word recognition, visual imagery, retrieving associated actions from LTM, word association | visual word recognition | visual grapheme recognition, conversion of graphemic to phonological code | retrieving and "reading" orthographic word patterns some semantic processing | auditory word perception or audio- phonological parsing, (articulatory loop rehearsal) |

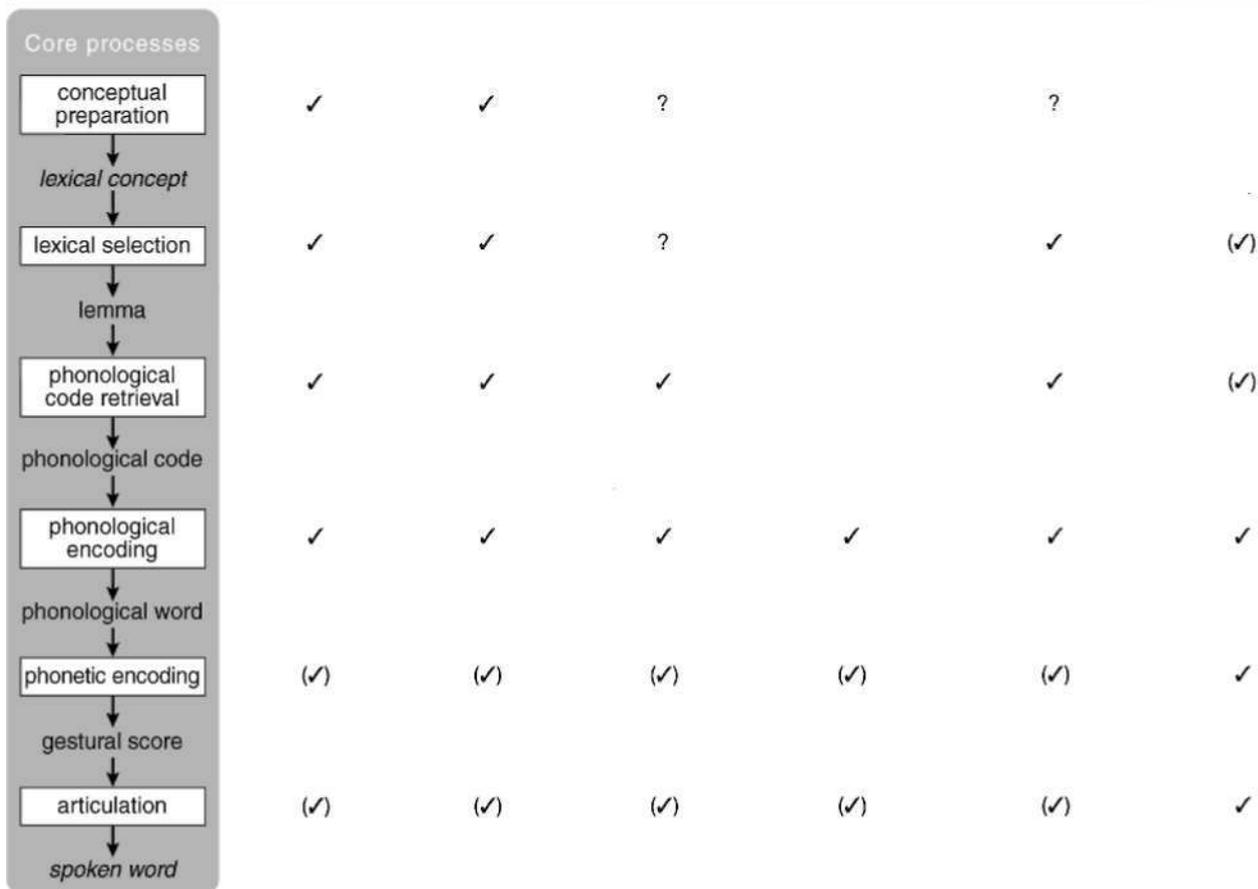


FIGURE 59.2 Core processing stages in the production of words and the involvement of core and lead-in processes in various word production tasks. A check mark indicates involvement of the component process in the task. A check mark

there is auditory feedback, triggering the speaker's normal word perception system. But there is feedback in silent word generation too, probably from the level of phonological word encoding.

The subsequent columns of figure 59.2 present a tentative analysis of the various word production tasks reviewed in this chapter. In particular, these columns mark the core processing components that are probably involved in these tasks. This aspect of the task analysis is relatively straightforward (though not at all inviolable). Much more problematic is the analysis of what we call

in parentheses indicates that the component's involvement depends on details of the task. Phonetic encoding and articulation, for instance, are involved in overt, but not in silent word production tasks.

the task's "lead-in." Different tasks enter the componential structure depicted in the left panel at different levels. In picture naming, for instance, the task enters the componential hierarchy from the very top component, conceptual preparation. The lead-in process is visual object recognition, which provides an object percept as input to conceptual preparation. Compare this to pseudoword reading. Here the hierarchy is probably entered at the level of phonological encoding—there is no accessing of a syntactic word or of a word's phonological code, but there is syllabification. The lead-in process is visual

orthographic analysis, some kind of bottom-up grapheme-to-phoneme mapping, which provides the ordered pattern of phonemes as input to syllabification. These lead-in processes are the real bottleneck for neuroimaging studies in word production. They are usually easily invented but ill-understood; still, they always contribute essentially to the neuroimaging results. Without serious behavioral research, one can only speculate at the processes involved in most task lead-ins. The top row of the columns in figure 59.2 provides some hunches about the lead-in processes involved in the various neuroimaging studies of word production. Here, we discuss just seven of them.

Picture naming Here the lead-in process is visual object recognition. It is the best understood lead-in process. Still, many variables are to be controlled, including visual complexity, perspectival orientation of the object, color versus black-and-white, and, of course, object category. All core components of word production are involved in picture naming.

Verb generation This task also involves all core components of word production, but the lead-in process is ill-understood (cf. Indefrey, 1997). The subject sees or hears a noun, which triggers a visual or auditory word recognition process. If the noun is a concrete one, the subject will probably generate a visual image; and, under the perspective of the task, that image activates one or more associated actions in long-term memory. These, then, guide the further conceptual preparation. When the noun is abstract, long-term memory may be accessed without visual imagery. But there are possible shortcuts, too. A perceived noun may directly activate a verbal concept or even a verb lemma by sheer association, as in *knife-cut*.

Noun generation The typical task here is to present a semantic category, such as “jobs” or “tools” or “animals,” and the subject is asked to generate as many exemplars as possible. It is a so-called “word fluency” task. The lead-in process may involve something as complicated as an imaginary tour, such as mentally touring a zoo, or it may be a much lower-level process, such as word association. And the subject’s strategy may differ rather drastically for different semantic categories. But it is quite likely that, at least from lexical selection on, all core processes of word generation are involved.

Generating words from beginning letter(s) The lead-in process is quite enigmatic. The letter “a” is a preferred stimulus. Like most other letters, it does not represent a unique phoneme in English, and the task probably capi-

talizes on visual word imagery. We can apparently retrieve orthographic word patterns beginning with “a.” The same holds for so-called “stem completion”—transforming a word-beginning like “gre-” to its completed form “green.” These visually imaged patterns are then “read,” occasionally involving some semantic activation. From there on, we are back to the core process, somewhere beginning at morphological or phonological encoding.

Word repetition The subject repeats a heard word. The lead-in process involves auditory word recognition, at least to some extent. We can repeat words we don’t understand (and nonwords for that matter); hence it suffices to have the phonological parse of the word. From there, the core process can be triggered at the level of phonological encoding (we must syllabify the word). Still, the lead-in process may be a lot richer, involving activation of the full lexical concept. In delayed word repetition tasks, an “articulatory loop” is involved—the subject rehearses the word during the delay.

Word reading The lead-in process is visual word recognition, which is complicated enough by itself. The core process may start at the low level of phonological encoding, from the set of activated phonemes (the phonological route); or it may start all the way up from the activated lexical concept (the semantic route). The strategy may differ from subject to subject, even from word to word.

Pseudoword reading Here, only the phonological route is available after the visual lead-in process. Although nonwords can have morphology (as in “*Jabberwocky*”), that was never the case in the tasks reviewed here. Hence, phonological encoding is the first core process in a pseudoword reading task.

In the following we will, to the best of our abilities, acknowledge the components involved in both the experimental word production tasks and their controls. But given the present state of the art, this is not always possible.

Cerebral localizations for word production— A meta-analysis

Research on brain regions involved in word production has been carried out with a wide variety of techniques. Among these are the study of brain lesions, direct cortical electrical stimulation, cortical stimulation by means of implanted subdural electrode grids, recording and source localization of event-related electrical and magnetic cortical activity (ERP, MEG, subdural electrode grids, single-cell recordings), and measurement of re-

gional cerebral metabolic and blood flow changes (PET, fMRI). Clearly, these techniques have contributed to our present knowledge on the neural substrates of single word production in different ways. Take cortical stimulation for example. Usually applied in the context of impending surgical interventions, cortical stimulation has provided evidence on loci which, when temporarily inactivated, impair word production—i.e., loci that are in some way necessary for the production process. But this technique is applied only to locations where language-related sites are suspected and then only to the limited part of the cortex that is exposed. In contrast, PET and fMRI can, in principle, reveal all areas that are more strongly activated during word production—including areas that may not be essential to the process and/or those whose impairment leads to no detectable difference in performance. ERP and MEG have provided preliminary insights in the temporal course of cortical activations. The sources of event-related electrical or magnetic activations can be localized. There are, however, limitations inherent in the mathematical procedures involved, so that, at present, the spatial information provided by these methods is considered less reliable. Due to the nature of the signal, subcortical structures are largely invisible to electrophysiological methods.

The purpose of this section is to combine the evidence provided by all these techniques and to give an overview of the localization (and to some extent the temporal order) of cerebral activations during word production. Furthermore, we will try to identify the neural substrates of the different processing components laid out in the previous section. To this end, we analyze the data reported in a large number of studies according to the following heuristic principle: If, for a given processing component, there are subserving brain regions, then these regions should be found active in all experimental tasks sharing the processing component, whatever other processing components these tasks may comprise. In addition, the region(s) should not be active in experimental tasks that do not share the component.

This approach allows for the isolation of processing components between studies even if isolation within single studies is not possible due to the difficulty in controlling for lead-in processes. Nevertheless, four conditions must be met. First, the processing components must be independently defined, so that their absence or presence can be evaluated for every experiment by applying the same criteria (which may differ from the author's criteria). Second, the task and control conditions must be heterogeneous enough across different experiments to ensure that a specific processing component is the only shared component. Third, the task and control condi-

tions must be heterogeneous enough across different experiments to ensure that for every processing component there is a different set of tasks that share the component. Fourth, the data base must be large, comprising enough experiments for a reliable identification of activations typically found for the different tasks. For word production these requirements seem to be sufficiently met, considering that word production tasks have been among the most frequently applied language tasks in neurocognitive research.

PROCEDURE We analyzed the cerebral localization data from 58 word production experiments (table 59.1). Our focus was on the core process of word production; thus, we excluded experiments reporting enhanced cerebral activations during word production tasks relative to control tasks that comprised most or all of the word production process—reading aloud, for example (Petersen et al., 1989; Raichle et al., 1994; Buckner, Raichle, and Petersen, 1995; Snyder et al., 1995; Fiez et al., 1996; Abdullaev and Posner, 1997), or object naming (Martin et al., 1995). Nor did our approach allow for inclusion of experiments or task comparisons focusing on the relative strengths of components of the word production process—comparisons of reading regularly spelled versus irregularly spelled words, for example (Herbster et al., 1997). Activations of these two tasks relative to baseline, however, were included. It was assumed throughout that the reported activation foci reflected true increases during the tasks rather than decreases during the baseline conditions.

Combining data from different techniques made it necessary to find a common term for cerebral localizations observed in relation to certain tasks. Since the majority of experiments employed PET or fMRI, we will use the terms “activations” or “activated areas,” extending that usage to EEG and MEG sources and to sites where cortical stimulation or lesions interfere with certain functions. We are aware that, for the latter case, one can at best infer that such locations are “active” in normal functioning.

The double reference system for anatomical localizations adopted here was used in order to capture data on the localization of cerebral activations stemming from methods with different resolution. On a gross level, comparable to a high degree of filtering, the reported loci were coded in a descriptive reference system dividing the cerebral lobes into two or three rostrocaudal or mediolateral segments of roughly equal size. Activations of cingulate, insula, and cerebellum were only differentiated in left and right. The segment labels were defined in terms of Talairach coordinates as given in table 59.2 (top).

TABLE 59.1
Overview of experiments included in the word production data set

| Task | Authors, methods, control conditions | | | |
|--------------------------------------|--|--|--|---|
| Picture naming aloud | Ojemann (1983) Cortical/thalamic stimulation | Ojemann et al. (1989) Cortical stimulation | Schäffler et al. (1993) Cortical stimulation | Crone et al. (1994) Subdural grid |
| | Haglund et al. (1994) Cortical stimulation | Salmelin et al. (1994) MEG | Abdullaev & Melnichuk (1995) Single-cell recordings, blank screen | |
| | Bookheimer et al. (1995) PET, nonsense drawings | Damasio et al. (1996) Lesion data | Damasio et al. (1996) PET, "faces," up/down | Levelt et al. (1998) MEG |
| Picture naming silent | Bookheimer et al. (1995) PET, nonsense drawings | Martin et al. (1996) PET, nonsense objects | Price, Moore, et al. (1996) PET, objects, "yes" | |
| Word generation silent, verbs | Wise et al. (1991) PET, rest | Crivello et al. (1995) PET, rest | Poline et al. (1996) PET, rest | Warburton et al. (1996) Exp. 1B, 2B+C, 3A (4) PET, rest |
| Word generation silent, nouns | Warburton et al. (1996) PET, rest | Paulesu et al. (1997) fMRI, rest | | |
| Generation from initial letter(s) | Aloud: Buckner, Raichle, & Petersen (1995) PET, silent fixation | | Silent: Paulesu et al. (1997) fMRI, rest | |
| Word reading aloud | Ojemann (1983) Cortical stimulation | Howard et al. (1992) PET, false fonts, "crime" | Sakurai et al. (1992) PET, fixation | Sakurai et al. (1993) PET, fixation |
| | Price et al. (1994) PET, false fonts, "ab-/present" | Bookheimer et al. (1995) PET, nonsense drawings | Price, Moore, & Frackowiak (1996) PET, rest | |
| | Gordon et al. (1997) Cortical stimulation | Herbster et al. (1997) Regular and irregular words (2) PET, letter strings, "hiya" | | Rumsey et al. (1997) PET, fixation |
| Word reading silent | Petersen et al. (1989) PET, fixation | Petersen et al. (1990) PET, fixation | Bookheimer et al. (1995) PET, nonsense drawings | Menard et al. (1996) PET, xxXxx |
| | Price, Moore, & Frackowiak (1996) PET, rest | Beauregard et al. (1997) Concrete, abstract, emotional words (3) PET, word reading instructions + fixation | | Hagoort et al. (1999) PET, fixation |
| Pseudoword reading aloud | Sakurai et al. (1993) PET, fixation | Indefrey et al. (1996) PET, false font strings | Herbster et al. (1997) PET, letter strings, "hiya" | Rumsey et al. (1997) PET, fixation |
| Pseudoword reading silent | Petersen et al. (1990) PET, fixation | Fujimaki et al. (1996) MEG | Hagoort et al. (1999) PET, fixation | |
| Word repetition aloud | Petersen et al. (1989) PET, silent listening | Howard et al. (1992) PET, reversed words, "crime" | | Crone et al. (1994) Subdural grid |
| | Price et al. (1996b) PET, rest | Gordon et al. (1997) Cortical stimulation | | |
| Pseudoword repetition silent | Warburton et al. (1996) PET, rest | | | |

More detailed anatomical references were additionally coded on a finer level in terms of gyri and subcortical structures following Talairach and Tournoux (1988). At this level, cingulate, insular, and cerebellar activations were further differentiated descriptively (table 59.2, bottom). In this way, it was possible to capture the fact that a PET activation focus reported as, for example, left inferior temporal gyrus, BA 37, would be consistent with electrophysiological data reporting a posterior temporal source localization or with patient data reporting a left posterior temporal lesion. Note that the sum of activations on the detailed level does not equal the number of activations on the gross level. A location, for example, that was reported as posterior temporal would be marked only on the gross level. Conversely, two posterior temporal locations in the superior and middle temporal gyrus were marked as such on the detailed level but only once on the gross level.

The studies included in this meta-analysis were not given any weights reflecting reliability differences due to design or size. This means that a certain degree of overlap of activations between studies was considered meaningful, but should not be interpreted as statistically significant. Nonetheless, the notion of “meaningfulness” was not totally arbitrary, but based on the following quasi-statistical estimate: At the gross level of description, there were on average 6.5 activation sites reported per experiment. Given that on this level of description

there were 28 regions of interest, any particular region had a chance of less than one-fourth to be reported as activated if reports were randomly distributed over regions. At the finer level of description, the average number of reported activation sites per experiment was 8.8 and there were 104 regions of interest; thus each had a chance of less than one-tenth to be reported as activated. Assuming these probabilities, the chance level for a region to be reported as activated in a number of studies was given by a binomial distribution. We rejected the possibility that the agreement of reports about a certain region was coincidental if the chance level was less than 10%. At the finer level of description, this corresponded to minimally two reported activations for regions covered by less than six experiments, minimally three reported activations for regions covered by six to eleven experiments, and so forth (4 out of 12–18; 5 out of 19–25; 6 out of 26–32). Note that for regions covered by many experiments a relatively smaller number of positive reports was required to be above chance (comparable to the fact that getting a 6 five times with ten dice throws is less likely than getting one 6 with two dice throws). But this criterion does not mean that atypical findings of activations in any single study are necessarily coincidental. In most cases, the number of experiments *not* reporting activations was not sufficient to consider a region as inactive at the chosen error probability level. Rare observations do not,

TABLE 59.2
Definition of descriptive anatomical labels

| Subdivisions of cortical lobes at grosser level of description | | | |
|---|-----------------------|-----------|----------------------|
| Frontal | | Temporal | |
| Anterior | $y > 34$ | Anterior | $y > -7$ |
| Posterior | $34 \geq y \geq 0$ | Mid | $-7 \geq y \geq -38$ |
| Motor (approx.) | $y < 0$ | Posterior | $y < -38$ |
| Parietal | | Occipital | |
| Sensory (approx.) | $y > -23$ | Medial | $x \leq 25 $ |
| Anterior | $-23 \geq y \geq -48$ | Lateral | $x > 25 $ |
| Posterior | $y < -48$ | | |
| Subdivisions of cingulum, insula, and cerebellum at finer level of description | | | |
| Cingulum | | Insula | |
| Anterior | $y > 12$ | Anterior | $y > 0$ |
| Mid | $12 \geq y \geq -24$ | Posterior | $y \leq 0$ |
| Posterior | $y < -24$ | | |
| Cerebellum | | | |
| Medial | $x \leq 20 $ | | |
| Lateral | $x > 20 $ | | |

therefore, exclude the possibility that a region is active. They may, for example, reflect smaller activations that are only detectable with refined techniques or better scanning devices.

A second, related point is that the nature of the data does not allow for an interpretation in terms of relative strengths of activations of certain areas. It is known that parameters such as item duration and frequency strongly influence the resulting pattern of activations (Price et al., 1994; Price, Moore, and Frackowiak, 1996). It is thus possible that areas are more frequently found active in some tasks, because their "typical" item durations and frequencies are higher or lower than in other tasks. It seems wise not to overinterpret the data, given that there is a considerable variability of these parameters across the studies of our data base; also, the interactions of these parameters with other experimental factors are largely unknown.

LEAD-IN PROCESSES According to our task analysis, nonshared activations in picture naming and word generation (table 59.3, first two columns) cannot be related to the core process of word production. The two tasks differ not only with respect to their lead-in processes but also with respect to the processes of phonetic encoding and articulation, given that word generation was performed silently in all experiments of the data set, whereas the majority of picture naming experiments involved overt articulation with silent control tasks (see table 59.1). Hence, to study the lead-in processes of picture naming, we must take into account activations that were specific for picture naming when compared to word generation and at the same time were not specific for overt (in contrast to silent) naming in general (table 59.3, last two columns). Although such lead-in activations were fairly numerous, we cover only the two most conspicuous sets here.

Six regions were reported as activated during word generation but rarely activated during picture naming: the left anterior superior frontal gyrus, the right anterior insula, the right mid superior and middle temporal gyri, the left caudate nucleus, and the right thalamus. While activations of the left anterior frontal and middle temporal gyri, right anterior insula, and left caudate seem to be specifically related to lead-in processes of word generation (see also Fiez, Raichle, and Petersen, 1996), the case is different for the right mid superior temporal gyrus and the right thalamus, which are also found in word reading.

Ten regions were activated during picture naming but not or only rarely during word generation: the left anterior insula, the left posterior inferior temporal and fusiform gyri, the medial occipital lobe bilaterally, the right

caudate nucleus, the left midbrain, and the medial and right lateral cerebellum (see, however, Fiez and Raichle, 1997, for evidence on right cerebellar activations in word generation when directly compared with word reading or picture naming). Five of these—the left anterior insula, the left posterior fusiform gyrus, the left and right medial occipital lobe, and the right medial cerebellum—were also found active in word reading, suggesting an involvement in visual processing, the principal lead-in component of picture naming and reading. Taking into account that activations of the posterior fusiform gyrus or the insula were not reported for pseudoword reading, it seems that these two areas may play a role at later visual processing stages, such as the retrieval of visual word forms or object patterns (cf. Sergent, Ohta, and MacDonald, 1992). In contrast, medial occipital activations observed during word and pseudoword reading are demonstrably due to the processing of nonlinguistic visual features of word-like stimuli, such as string length (Beauregard et al., 1997; Indefrey et al., 1997).

THE CORE PROCESS OF WORD PRODUCTION According to our task analysis, picture naming and word generation are the two tasks that include all components of word production. The set of regions reported as activated for both tasks (table 59.3, first two columns) can be considered as being related to the core process of word production up to and including phonological encoding. This word production network is strictly left-lateralized, and consists of the posterior inferior frontal gyrus (Broca's area), the mid superior and middle temporal gyri, the posterior superior and middle temporal gyri (Wernicke's area), and the left thalamus.

By taking into account further tasks that enter the word production process at different stages, we now attempt to identify the subprocesses to which these regions are particularly sensitive.

Conceptual preparation and lexical selection The activation of a lexical concept and the subsequent selection of the corresponding lemma are processes that are shared by picture naming and word generation but not necessarily by word reading. The synopsis of reported results yielded one area within the word production network—the mid segment of the left middle temporal gyrus—that has been found activated during picture naming and word generation, but less so during word reading. This area is the best candidate for a neural correlate of conceptual and/or lexical selection processes in word production. The mid part of the left middle temporal gyrus has been found as part of a "common semantic system" in a study (Vandenberghe et al., 1996) involving word and object stimuli. This finding is compatible with a role of this region in conceptual

TABLE 59.3
Synopsis of cerebral localizations for word production tasks*

| Task | Picture naming | Word generation | Word reading | Pseudo-word reading | Word generation from initial letter(s) | Word repetition | Pseudo-word repetition | All tasks aloud/silent control | All tasks silent or aloud control | |
|-----------------|----------------|-----------------|--------------|---------------------|--|-----------------|------------------------|--------------------------------|-----------------------------------|-------|
| No. of studies | 14 | 9 | 20 | 7 | 2 | 5 | 1 | 25 | 33 | |
| Temporal | | | | | | | | | | |
| R | Anterior | 1/9 | | | | | 1/1 | | 2/32 | |
| | GTs | 1/9 | | | | | 1/1 | | 2/32 | |
| | GTm | | | | | | | | | |
| | GTi | | | | | | | | | |
| | Mid | 2/9 | 7/9 | 5/18 | 4/7 | | 2/3 | 1/1 | 10/16 | 11/32 |
| | GTs | 1/9 | 5/9 | 5/18 | 3/7 | | 2/3 | 1/1 | 10/16 | 7/32 |
| | GTm | | 6/9 | 2/18 | | | 1/3 | | 3/16 | 6/32 |
| | GTi | | | | | | | | | |
| | GF | | | 1/18 | 1/7 | | | | 1/16 | 1/32 |
| | Gh | 1/9 | | | | | | | | 1/32 |
| | Posterior | 2/9 | | 5/18 | 1/7 | | 1/3 | | 4/16 | 5/32 |
| | GTs | | | 2/18 | 1/7 | | 1/3 | | 2/16 | 2/32 |
| | GTm | | | 1/18 | 1/7 | | | | | 2/32 |
| | GTi | | | 2/18 | | | | | 2/16 | |
| | GF | 2/9 | | 2/18 | | | | | 1/16 | 3/32 |
| GL | | | 1/18 | | | | | | 1/32 | |
| L | Anterior | 5/12 | 1/9 | 2/18 | | | | 4/18 | 5/33 | |
| | GTs | 5/12 | 1/9 | 1/18 | | | | 4/18 | 4/32 | |
| | GTm | 1/12 | | | | | | 1/18 | | |
| | GTi | 1/12 | | 1/18 | | | | 1/18 | 1/32 | |
| | Mid | 9/13 | 6/9 | 13/20 | 5/7 | | 3/5 | 1/1 | 17/23 | 20/33 |
| | GTs | 6/13 | 3/9 | 10/20 | 5/7 | | 3/5 | 1/1 | 17/23 | 11/33 |
| | GTm | 5/13 | 5/9 | 4/20 | 2/7 | | 2/5 | | 6/23 | 12/33 |
| | GTi | 1/12 | | 1/20 | | | | | | 2/33 |
| | GF | 2/11 | | 4/20 | | | | | 2/21 | 5/33 |
| | Gh | 1/10 | | 1/20 | | | | | | 2/33 |
| | Posterior | 11/12 | 6/9 | 17/20 | 2/7 | | 3/5 | 1/1 | 17/22 | 23/33 |
| | GTs | 6/12 | 4/9 | 6/20 | | | 3/5 | | 12/22 | 7/33 |
| | GTm | 4/12 | 4/9 | 5/20 | | | | | 5/22 | 8/33 |
| | GTi | 3/11 | 1/9 | 3/18 | 1/7 | | | 1/1 | 3/18 | 6/33 |
| | GF | 3/10 | 1/9 | 7/18 | | | | | 3/18 | 8/33 |
| GL | | | 2/18 | 1/7 | | | | | 3/33 | |

(continued)

TABLE 59.3 *Continued*

| Task | Picture naming | Word generation | Word reading | Pseudo-word reading | Word generation from initial letter(s) | Word repetition | Pseudo-word repetition | All tasks aloud/silent control | All tasks silent or aloud control |
|----------------|----------------|-----------------|--------------|---------------------|--|-----------------|------------------------|--------------------------------|-----------------------------------|
| No. of studies | 14 | 9 | 20 | 7 | 2 | 5 | 1 | 25 | 33 |
| Frontal | | | | | | | | | |
| R | Anterior | 1/9 | 1/18 | | | | | | 2/32 |
| | GFs | | | | | | | | |
| | GFm | 1/9 | | | | | | | 1/32 |
| | GFi | | 1/18 | | | | | | 1/32 |
| | GFd, GO | | | | | | | | |
| | Posterior | 3/6 | 3/9 | 1/18 | 1/7 | | | 3/14 | 5/32 |
| | GFs | | | | | | | | |
| | GFm | | 2/9 | | | | | | 2/32 |
| | GFi | 1/5 | 2/9 | 1/18 | 1/7 | | | 2/14 | 3/32 |
| | GR, Gs | | | | | | | | |
| | Motor | 2/6 | 5/9 | 5/18 | 3/7 | 2/3 | | 10/14 | 7/32 |
| | ventral GPrC | 1/6 | | 4/18 | 2/7 | 2/3 | | 8/14 | 1/32 |
| | dorsal GPrC | 1/6 | | 3/18 | 1/7 | | | 3/14 | 2/32 |
| | SMA | | 5/9 | 4/18 | | 2/3 | | 5/14 | 6/32 |
| L | Anterior | | 3/9 | 3/18 | | | | | 6/32 |
| | GFs | | 3/9 | 1/18 | | | | | 4/32 |
| | GFm | | 2/9 | 1/18 | | | | | 3/32 |
| | GFi | | 1/9 | | | | | | 1/32 |
| | GFd, GO | | 1/9 | 1/18 | | | | | 2/32 |
| | Posterior | 8/10 | 9/9 | 11/20 | 3/7 | 2/2 | 2/5 | 1/1 | 14/22 |
| | GFs | 1/8 | 2/9 | | | | 1/5 | 2/20 | 2/32 |
| | GFm | 2/8 | 4/9 | 4/20 | | | | 1/20 | 9/32 |
| | GFi | 5/9 | 9/9 | 9/20 | 3/7 | 2/2 | 1/5 | 1/1 | 11/21 |
| | GR, Gs | | | | | | | | 18/32 |
| | Motor | 5/10 | 7/9 | 7/20 | 3/7 | 2/5 | 1/1 | 13/22 | 12/32 |
| | ventral GPrC | 4/10 | 1/9 | 6/20 | 3/7 | 2/5 | 1/1 | 11/22 | 6/32 |
| | dorsal GPrC | 2/9 | 1/9 | 3/18 | | 1/4 | | 5/18 | 2/32 |
| | SMA | 2/6 | 7/9 | 4/18 | 1/7 | 1/4 | | 8/15 | 8/32 |
| Insula | | | | | | | | | |
| | R | | 5/9 | 3/18 | 1/7 | 1/3 | 1/1 | 3/13 | 8/32 |
| | anterior | | 5/9 | 2/18 | 1/7 | 1/3 | 1/1 | 2/13 | 8/32 |
| | posterior | | | 1/18 | | 1/3 | | 2/13 | |
| | L | 3/6 | 1/9 | 6/18 | | 1/1 | 2/3 | 1/1 | 6/13 |
| | anterior | 3/6 | 1/9 | 6/18 | | 1/1 | 2/3 | 1/1 | 6/13 |
| | posterior | | | | | | | | 8/32 |

TABLE 59.3 *Continued*

| Task | | Picture naming | Word generation | Word reading | Pseudo-word reading | Word generation from initial letter(s) | Word repetition | Pseudo-word repetition | All tasks aloud/silent control | All tasks silent or aloud control |
|-----------------|--------------|----------------|-----------------|--------------|---------------------|--|-----------------|------------------------|--------------------------------|-----------------------------------|
| No. of studies | | 14 | 9 | 20 | 7 | 2 | 5 | 1 | 25 | 33 |
| Parietal | | | | | | | | | | |
| R | Sensory | 1/7 | | 3/18 | 1/7 | | 1/3 | | 5/14 | 1/32 |
| | ventral GPoC | 1/7 | | 3/15 | 1/7 | | 1/3 | | 5/11 | 1/32 |
| | dorsal GPoC | | | | | | | | | |
| | Anterior | | | 2/18 | | | | | 1/14 | 1/32 |
| | LPi | | | 2/15 | | | | | 1/11 | 1/32 |
| | LPs | | | | | | | | | |
| | PCu | | | | | | | | | |
| | Posterior | 3/7 | | 3/18 | 1/7 | | | | 4/14 | 3/32 |
| | LPi | | | | | | | | | |
| | LPs | 1/7 | | | 1/7 | | | | | 2/32 |
| Gsm | 1/7 | | | | | | | 1/11 | | |
| Ga | 1/7 | | | | | | | 1/11 | | |
| PCu | | | 1/15 | | | | | | 1/32 | |
| L | Sensory | 3/9 | | 5/20 | 1/7 | | 1/4 | | 8/19 | 2/32 |
| | ventral GPoC | 3/9 | | 5/17 | 1/7 | | 1/4 | | 8/16 | 2/32 |
| | dorsal GPoC | | | | | | | | | |
| | Anterior | 2/9 | | 3/20 | | | | | 3/19 | 2/32 |
| | LPi | 2/9 | | 3/17 | | | | | 3/16 | 2/32 |
| | LPs | | | | | | | | | |
| | PCu | | | | | | | | | |
| | Posterior | 3/8 | 2/9 | 4/20 | | | | | 5/18 | 4/32 |
| | LPi | | | | | | | | | |
| | LPs | | | | | | | | | |
| Gsm | 1/7 | 1/9 | 1/17 | | | | | 2/15 | 1/32 | |
| Ga | 1/6 | 1/9 | 1/17 | | | | | 2/14 | 1/32 | |
| PCu | | | | | | | | | | |
| Cingulum | | | | | | | | | | |
| R | | | 1/9 | 2/18 | 2/7 | | | | 1/13 | 4/32 |
| | anterior | | 1/9 | 2/18 | | | | | 1/13 | 2/32 |
| | mid | | | | 2/7 | | | | | 2/32 |
| | posterior | | | | 1/7 | | | | | 1/32 |
| L | | 2/6 | 3/9 | 5/18 | 4/7 | | | | 5/13 | 9/32 |
| | anterior | 2/6 | 2/9 | 4/18 | | | | | 3/13 | 5/32 |
| | mid | | | 2/18 | 4/7 | | | | 2/13 | 4/32 |
| | posterior | | 1/9 | 1/18 | 1/7 | | | | | 3/32 |

(continued)

TABLE 59.3 *Continued*

| Task | | Picture naming | Word generation | Word reading | Pseudo-word reading | Word generation from initial letter(s) | Word repetition | Pseudo-word repetition | All tasks aloud/silent control | All tasks silent or aloud control |
|-------------------------------|--------------|----------------|-----------------|--------------|---------------------|--|-----------------|------------------------|--------------------------------|-----------------------------------|
| No. of studies | | 14 | 9 | 20 | 7 | 2 | 5 | 1 | 25 | 33 |
| Occipital | | | | | | | | | | |
| R | Medial | 4/6 | | 7/18 | 3/7 | | 1/3 | | 7/13 | 8/32 |
| | Sca | | | | | | 1/3 | | | 1/30 |
| | Cu | | | | 1/7 | | 1/3 | | 1/8 | 1/30 |
| | GL | | | 5/15 | 1/7 | | | | 1/8 | 5/30 |
| | GF | | | 2/15 | | | | | 1/8 | 1/30 |
| | Lateral | 1/6 | | 3/18 | 1/7 | | | | 4/13 | 1/32 |
| | GOs,m,i | | | 1/15 | | | | | | 1/30 |
| L | Medial | 5/6 | 1/9 | 8/18 | 4/7 | | | | 8/13 | 11/32 |
| | Sca | 2/3 | 1/9 | 1/15 | | | | | 1/10 | 3/30 |
| | Cu | | | | 1/7 | | | | 1/10 | |
| | GL | 1/3 | | 5/15 | 2/7 | | | | 2/10 | 6/30 |
| | GF | 1/3 | | 2/15 | 1/7 | | | | 3/10 | 1/30 |
| | Lateral | 2/6 | 1/9 | 6/18 | 1/7 | | | | 3/13 | 7/32 |
| | GOs,m,i | 1/3 | | 4/15 | | | | | | 5/30 |
| Subcortical structures | | | | | | | | | | |
| R | Caudate | 2/5 | 1/9 | | | | | | 1/12 | 2/31 |
| | NL | 1/4 | 1/9 | 2/18 | | | | | 2/11 | 2/31 |
| | Thalamus | 1/5 | 4/9 | 5/18 | 1/7 | | 1/3 | | 6/12 | 6/31 |
| | Hypothalamus | | | | | | | | | |
| | Midbrain | 1/4 | 1/9 | 1/18 | | | | | 2/11 | 1/31 |
| | Hippocampus | | | | | | | | | |
| L | Caudate | 1/4 | 3/9 | 1/18 | | | | | 1/12 | 4/31 |
| | NL | 1/4 | 2/9 | 4/18 | | | | | 1/11 | 6/31 |
| | Thalamus | 4/5 | 6/9 | 5/18 | 2/7 | 1/1 | 1/3 | | 9/12 | 10/31 |
| | Hypothalamus | | | | | | | | | |
| | Midbrain | 2/4 | 1/9 | 2/18 | | | | | 2/11 | 3/31 |
| | Hippocampus | 1/4 | | 2/18 | | | | | 1/11 | 2/31 |
| Cerebellum | | | | | | | | | | |
| | R | 3/4 | 1/9 | 7/18 | 3/7 | | 1/3 | | 8/11 | 7/31 |
| | medial | 2/4 | 1/8 | 4/16 | 3/6 | | 1/3 | | 7/9 | 4/30 |
| | lateral | 3/4 | 1/8 | 3/16 | 2/6 | | | | 3/9 | 6/30 |
| | L | 2/4 | 2/9 | 3/18 | 4/7 | | 1/3 | | 7/11 | 5/31 |
| | medial | 2/4 | | 2/16 | 2/6 | | 1/3 | | 5/9 | 2/30 |
| | lateral | 1/4 | 1/8 | 2/16 | 3/6 | | | | 5/9 | 2/30 |

*The number of activations reported for a region is given in proportion to the number of studies covering it. Relative cell frequencies exceeding the error probability threshold of $p < .1$ are printed in bold. Data were collapsed with respect to overt versus silent responses in the last two columns. Aloud tasks with aloud control conditions are grouped with silent tasks.

Key: Except for SMA (= supplementary motor area), the abbreviations of gyri and subcortical structures follow Talairach and Tournoux (1988): GFs, GFm, GFi = superior, middle, and inferior frontal gyrus; GFd = medial frontal gyrus; GO = orbital gyri; GR = gyrus rectus; Gs = gyrus subcallosus; GPrC = precentral gyrus; GTs, GTm, GTi = superior, middle, and inferior temporal gyrus; GF = fusiform gyrus; Gh = parahippocampal gyrus; GL = lingual gyrus; GpoC = postcentral gyrus; LPs, LPi = superior and inferior parietal lobule; PCu = precuneus; Gsm = supramarginal gyrus; Ga = angular gyrus; Sca = calcarine sulcus; Cu = cuneus; GOs, GOm, GOi = superior, middle, and inferior occipital gyri; NL = lenticular nucleus.

processing. It should, however, be kept in mind that the activation of a lexical concept for word production is only one very specific conceptual process among many other conceptual-semantic processes. It is, more precisely, to be distinguished from the semantically guided search processes in word generation (possibly subserved by anterior frontal regions), as well as from prelinguistic conceptual processes involved in object recognition and categorization [possibly subserved by the ventral temporal lobe and a heterogeneous set of category-specific regions (cf. Martin et al., 1995, 1996; Damasio et al., 1996; Beauregard et al., 1997)]. As far as the core process of word production is concerned, these conceptual processes are to be considered as lead-in processes.

Phonological code retrieval Lexical word form retrieval takes place in picture naming, word generation, and word reading, but not in pseudoword reading. This pattern is found in the reports on activations of the left posterior superior and middle temporal gyri, i.e., Wernicke's area, and the left thalamus. The posterior superior temporal lobe has also been found active during word comprehension (Price, Wise, et al., 1996). It is thus conceivable that a common store of lexical word form representations is accessed in word production and comprehension.

Phonological encoding All tasks, including word repetition and pseudoword reading, involve the production of phonological words. Neural structures subserving this process should consequently be found active throughout. No region fulfills this requirement perfectly, but the left posterior inferior frontal gyrus (Broca's area) and the left mid superior temporal gyrus come very close. Both regions just miss our criterion for a meaningful number of activations in tasks for which there are only few studies in the data set (word repetition, word generation from initial letters). Cabeza and Nyberg (1997) reviewed one repetition and two reading aloud experiments with Broca's area as the only active region in common. According to our task analysis, the only common processing component was indeed phonological encoding.

Broca's area has been observed to be active not only during explicit but also during implicit processing of pseudowords (performing a feature detection task; Frith et al., 1995; Price, Wise, and Frackowiak, 1996). The left mid superior temporal gyrus, however, was not found active in these studies, which may indicate a functional difference between the two areas within nonlexical phonological processing.

Broca's area is, furthermore, known to be activated in tasks involving phonological processing in language comprehension (Démonet et al., 1992, 1996; Zatorre et al., 1992; Fiez and Raichle, 1997). The common denom-

inator of these observations and the activation of Broca's area in language production seems to be that this region is a nonlexical phonological processor.

Price and Friston (1997) presented a statistical method—conjunction analysis—to isolate common processing components between different experiments. They used this method to identify a processing component, which they called phonological retrieval, across four word production experiments. The following areas were reported to be related to this processing component: the left posterior basal temporal lobe BA 37 (this area corresponds to the fusiform gyrus in our terminology), the left frontal operculum, the left thalamus, and the midline cerebellum. Given that “phonological retrieval” according to our analysis corresponds to the two processing stages of phonological code retrieval and phonological encoding, the observed activations of the left thalamus and the left frontal operculum are in good agreement with the results we obtained here on the basis of a large number of reported experiments. The other two areas according to our analysis subserve a high-level visual lead-in process and the articulatory process. Price and Friston (1997) assume these processes to be shared by the control conditions (viewing objects or strings of false fonts and saying “yes” to every stimulus), leaving only “phonological retrieval” as the common component of all task-control contrasts. It should, however, be noted that this assumption holds only if the contributions of these task components are constant in the active task and the baseline task. The authors themselves point out that this core assumption of the cognitive subtraction paradigm is problematic. Visual and motor-related activations have been observed to be modulated (e.g., by attention or response selection) in active relative to passive tasks (Friston et al., 1996; see also Shulman et al., 1997, for medial cerebellar activations in controlled motor response tasks). It is therefore not excluded that activations related to visual and articulatory processing were equally enhanced in all four active tasks and consequently not filtered out by the conjunction statistics.

Phonetic encoding and articulation Activations related to the production of the abstract articulatory program and its execution should be found in tasks with overt pronunciation and silent control conditions, but not in silent tasks or in tasks where articulation has been controlled for (table 59.3, last two columns). All aloud tasks with silent controls led to activations of primary motor and sensory areas, i.e., the right and left ventral (and, to some extent, dorsal) precentral gyri and the right and left ventral postcentral gyri; but in the group of silent or controlled aloud tasks, such activations were rarely reported. This finding was expected, since these areas are

known to be involved in the sensorimotor aspects of articulation. Hence, it provides independent validation for our analysis procedure. It can also be concluded that output control conditions such as saying the same word to every stimulus cancel out these sensorimotor activations effectively.

Further regions typically found in aloud but not in silent tasks were the left anterior superior temporal gyrus, the right SMA, and the left and medial cerebellum. The dissociation in cerebellar activity, with left and medial parts being closely linked to motor output, confirms an observation by Shulman and colleagues (1997); it is also discussed in a comprehensive review of cerebellar activations by Fiez and Raichle (1997).

Our survey shows a complex pattern of reports on left anterior temporal and SMA activations. Both regions are related to overt pronunciation, but seem to be task-sensitive as well. While the temporal area is most frequently reported in overt picture naming, SMA activations (left and right) seem to be rare in this task. Also, SMA activations, though more frequent for aloud tasks, are observed to some extent in silent tasks as well. The latter is not restricted to silent word production, but is also found in tasks involving verbal working memory or nonverbal imagination of movements (for a discussion, see Fiez and Raichle, 1997). It may be concluded that the SMA is in some complex way related to motor planning and imagination of articulation. Given that the instructions in what we have designated silent tasks ranged from mere “viewing” to “thinking” to silent “mouthing” of responses, it is not difficult to understand that the SMA involvement may vary to a great extent between tasks.

SUMMARY The word production network that has been identified on the basis of a substantial number of experiments makes sense. It is largely identical with the set of regions found to be necessary for picture naming in direct cortical stimulation studies. Given that these comprised but a minority of the experiments analyzed and furthermore concentrated on a single task, this is not a trivial result. It means that the neuroimaging studies, despite their heterogeneity of methods and tasks, captured the essential processes of word production. It also means that the cerebral structures subserving these processes can be successfully distinguished from the large number of cerebral activations related to task-specific and experiment-specific processes by an appropriate meta-analysis procedure. On the other hand, neither the network as a whole nor any single region was found activated in all experiments. There are a number of reasons for this. First, weaker activations may have been overlooked or not reported. In general, the statistical thresh-

olds applied in neuroimaging experiments tend to be conservative; moreover, some authors may have focused on robust findings, applying very strict statistical thresholds that rendered minor activations insignificant. There also was a tendency toward fewer activations in older studies, where the technology could not reliably detect as many activations. Second, although we focused on experiments with low-level control conditions, so that the word production process itself would not be obscured, we could not confidently eliminate this obscuring in all cases. Stereotype overt responses (for instance, a “yes” response on all trials) may be retrieved from an articulatory buffer, but may also be normally produced (as is the case with meaningful response alternatives, such as saying “up” or “down” depending on the orientation of the stimulus object in the baseline task)—thereby taking away at least part of the activations due to core word production processes. Considering these points, it would have been misleading to apply the above heuristic principle to every single experiment rather than to sets of experiments using similar tasks, as we have done here.

The time course of word production

TIME WINDOWS FOR COMPONENT PROCESSES Every processing stage of word production takes time. Furthermore, as the above analysis suggests, cortical areas involved in word production are specialists for certain processing components. Activations in these regions should, therefore, have temporal properties that are compatible with the durations of the different processing stages. Table 59.4 summarizes the small number of studies that, to date, have provided timing information related to cortical areas involved in word production. We compare these data with estimates for the processing stages in picture naming given by Levelt and colleagues (1998) based on work by Thorpe, Fize, and Marlot (1996), Levelt and colleagues (1991), Roelofs (1997), Wheeldon and Levelt (1995), and Van Turennout, Hagoort, and Brown (1997, 1998).

It is estimated that visual and conceptual processing are accomplished within the first 150 ms, and lexical selection within 275 ms from picture onset. As identified in the previous section, the corresponding cortical sites were the medial occipital lobe (bilaterally), the left medial posterior temporal lobe for visual processing, and the mid segment of the left middle temporal gyrus for conceptual preparation and lexical selection. The time windows given for occipital activations in table 59.4 are in good agreement with what is assumed for early visual processing. Inferior posterior temporal activations during reading also seem to occur

TABLE 59.4
*Time course of word production in relation to anatomical regions**

| Task | | Picture naming aloud | | | Word reading silent | Pseudoword reading silent | Word repetition aloud |
|-------------|-----------|----------------------------|------------------------|----------------------|------------------------------------|---------------------------|----------------------------|
| Studies | | Crone et al. (1994) | Salmelin et al. (1994) | Levelt et al. (1998) | Salmelin et al. (1996) | Fujimaki et al. (1996) | Crone et al. (1994) |
| | | Subdural grid | MEG | MEG | MEG | MEG | Subdural grid |
| Occipital R | medial | | 0–200 | 0–275 | 100–200 | | |
| | lateral | | | 0–275 | | | |
| L | medial | | | 0–275 | 100–200 | | |
| | lateral | | | 0–275 | | | |
| Parietal R | posterior | | 200–400 (Ga) | 150–275 (Gsm) | | >400 (cingulum) | |
| | anterior | | | | | >400 (cingulum) | |
| | sensory | | | 400–600 | | | |
| L | posterior | | 200–400 (Ga) | | | | |
| | anterior | | | | | | |
| | sensory | | | 400–600 | | | |
| Temporal R | posterior | | | | 100–200 (GTi) | <400 | |
| | mid | | 300–500 (GTs) | | | | |
| | anterior | | | | | | |
| L | posterior | 300–600 (GTs,GTm) | 200–400 (GTs) | 275–400 (GTs) | 100–200 (GTi) 200–400 (GTs,GTm) | | |
| | mid | 600–900 (GTs) | | 275–400 (GTs) | 200–400 (GTs,GTm) | <400 | 300–900 (GTs) |
| | anterior | | | | | | |
| Frontal R | motor | | 500–600 | | 200–400 | | |
| | posterior | | 200–400 | | | | |
| | anterior | | | | | | |
| L | motor | | 500–600 | | | | |
| | posterior | 300–900 (GF _i) | 200–400 | | | | 600–900 (GF _i) |
| | anterior | | | | | | |

*Time intervals are given in milliseconds; additional anatomical information is given in parentheses. Ga = angular gyrus; Gsm = supramarginal gyrus; GTs, GTm = superior, middle temporal gyrus; GF_i = inferior frontal gyrus.

in this time window (Salmelin et al., 1996). Instead of the expected middle temporal activation site, however, both Salmelin and colleagues (1994) and Levelt and colleagues (1998) identified dipoles in posterior parietal

regions, which have not been found active in PET studies.

Lexical phonological code retrieval and phonological encoding are estimated to take place between 275 and

400 ms. The corresponding cortical sites identified above were the left posterior superior and middle temporal gyri for accessing the form code, as well as the left posterior inferior frontal gyrus and the left mid superior temporal gyrus for phonological encoding. The time windows given in table 59.4 clearly support an involvement of Wernicke's area in word form retrieval. Further support comes from a study by Kuriki and colleagues (1996) reporting a time window of 210–410 ms in this region during a phonological matching task on syllabograms. The situation is less clear for phonological encoding, where both supporting and disagreeing time windows have been found for Broca's area and the mid segment of the left superior temporal lobe. The available data on the time course of word production thus support the localization studies with respect to lead-in processes and word form access. They are consistent with respect to phonological encoding, but raise doubt with respect to the cortical sites related to conceptual preparation and lemma access in word production.

INTEGRATING SPATIAL AND TEMPORAL INFORMATION Taking into account both the results of the previous section and the present data on the time course of word production, the following (tentative) picture of the spatial and temporal flow of activation in word production has emerged: In picture naming and probably also in word generation from visual stimuli (see Abdullaev and Posner, 1997) visual and conceptual lead-in processes involving occipital, ventrotemporal, and anterior frontal regions converge within 275 ms from stimulus onset on a lexical concept to be expressed. In addition, the best-fitting lexical item is selected within this period. The middle part of the left middle temporal gyrus may be involved in this conceptually driven lexical selection process. Within the following 125 ms, the activation spreads to Wernicke's area, where the lexically stored phonological code of the word is retrieved, and this information is relayed anteriorly to Broca's area and/or the left mid superior temporal lobe for post-lexical phonological encoding. Within another 200 ms, the resulting phonological word is phonetically encoded (with possible contributions of SMA and cerebellum to this or additional motor planning processes) and sensorimotor areas involved in articulation become active.

Syntactic production

Research on the neural correlates of syntactic processing has mainly concentrated on syntactic comprehension. Regions in and around Broca's area have been most frequently identified as being related to syntactic processing (Stowe et al., 1994; Indefrey et al., 1996;

Just et al., 1996; Stromswold et al., 1996). Caplan, Hildebrandt, and Makris (1996), on the other hand, did not find a significant difference in syntactic comprehension of agrammatic patients between anterior and posterior sylvian lesion sites in a thorough study involving a range of syntactic constructions. Just and colleagues (1996), too, found Wernicke's area (as well as the right-sided homologs of Broca's and Wernicke's area) to be sensitive to syntactic complexity. Two studies (Mazoyer et al., 1993; Dronkers et al., 1999) suggested a role for the left anterior superior temporal lobe in syntactic processing. The pseudoword sentence repetition task of Indefrey and colleagues (1996) comprised a syntactic production component in addition to syntactic parsing, and the resulting activation focus was more rostrally located (border of Broca's area and the adjacent middle frontal gyrus, BA 9) than the foci identified in pure comprehension tasks. Direct electrical stimulation of a similar site was found by Ojemann (1983) to interfere with the grammatically correct repetition of sentences. In the latter study, however, a number of perisylvian stimulation sites yielded the same effect, so that at present there is no real evidence for cortical areas specifically subserving syntactic production.

Self-monitoring

Self-monitoring (see figure 59.1) involves an *external loop*, taking as input the acoustic speech signal of the speaker's own voice, and an *internal loop*, taking as input the phonological score—i.e., the output of phonological encoding. The most economical assumption is that both loops enter the processing pathway that is used for normal speech comprehension (Levelt, 1989).

EXTERNAL LOOP There is evidence that hearing one's own voice while speaking induces the same temporal lobe activations as listening to someone else's voice (McGuire, Silbersweig, and Frith, 1996; Price, Wise, et al., 1996). McGuire, Silbersweig, and Frith, furthermore, were able to induce additional bilateral superior temporal activations by distorting the subjects' feedback of their own voices or presenting the subjects with alien feedback while they spoke. These results show that just as in listening to other people's speech (Démonet et al., 1992; Zatorre et al., 1992) attentional modulation of the activity of the temporal cortices in self-monitoring is possible.

INTERNAL LOOP McGuire and colleagues (1996) also provided some evidence that internal monitoring, too, makes use of a cortical area involved in speech

perception—more precisely, the left posterior superior temporal lobe. This area showed stronger activation (together with motor areas) when subjects imagined hearing another person's voice than when they spoke silently to themselves. It is not implausible that the observed blood flow increase was due to an attentional modulation of internal self-monitoring, although other explanations are possible as well.

Conclusion

Speaking involves substantially more than merely producing words. The recent neuroscience literature on speech production reviewed in this chapter is limited owing to its emphasis on word production. But this may well be a transient state of affairs. After all, the wealth of data that enabled the present meta-analysis derives from no more than a decade or so of neuroimaging research. We have an emerging picture now of the cerebral network that underlies the production of words. A crucial ingredient of this meta-analysis is the explicit, detailed functional theory of word production. It provided us with the framework for a componential task analysis and with time frame estimates for the component processes. No doubt, the same approach, applied to other aspects of speaking, will eventually lead to similar progress.

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