

56 Semantic Unification

PETER HAGOORT, GIOSUÈ BAGGIO, AND ROEL M. WILLEMS

ABSTRACT Language and communication are about the exchange of meaning. A key feature of understanding and producing language is the construction of complex meaning from more elementary semantic building blocks. The functional characteristics of this semantic unification process are revealed by studies using event-related brain potentials. These studies have found that word meaning is assembled into compound meaning in not more than 500 ms. World knowledge, information about the speaker, co-occurring visual input, and discourse all have an immediate impact on semantic unification and trigger electrophysiological responses that are similar to those triggered by sentence-internal semantic information. Neuroimaging studies show that a network of brain areas, including the left inferior frontal gyrus, the left superior/middle temporal cortex, the left inferior parietal cortex, and, to a lesser extent, their right-hemisphere homologues are recruited to perform semantic unification.

Ultimately, language is the vehicle for the exchange of meaning between speaker and listener, between writer and reader. The unique feature of this vehicle is that it enables the assembly of complex expressions from simpler ones. The cognitive architecture necessary to realize this expressive power is tripartite in nature, with levels of form (sound, graphemes, manual gestures in sign language), syntax, and meaning as the core components of our language faculty (Jackendoff, 1999, 2002; Levelt, 1999). The principle of compositionality is often invoked to characterize the expressive power of language at the level of meaning. The most strict account of compositionality states that the meaning of an expression is a function of the meanings of its parts and the way they are syntactically combined (Fodor & Lepore, 2002; Heim & Kratzer, 1998; Partee, 1984). In this account, complex meanings are assembled bottom-up from the meanings of the lexical building blocks by means of the combinatorial machinery of syntax. This process is sometimes referred to as simple composition (Jackendoff, 1997). That this is not without problems can be seen in adjective-noun constructions such as “flat tire,” “flat beer,” “flat note,” and so on (Keenan, 1979). In all these cases, the meaning of “flat” is quite different and strongly context dependent. For this and other reasons, simple composition seems not to hold across

all possible expressions in the language (for a discussion of this and other issues related to compositionality, see Baggio, van Lambalgen, & Hagoort, in press). One of the challenges for a cognitive neuroscience of language is to account for the functional and neuroanatomical underpinnings of online meaning composition. 1

In linking the requirements of the language system as instantiated in the finite and real-time machinery of the human brain to the broader domain of cognitive neuroscience, three functional components are considered to be the core of language processing (Hagoort, 2005). The first is the *memory* component, which refers to the different types of language information stored in long-term memory (the mental lexicon) and to how this information is retrieved (lexical access). The *unification* component refers to the integration of lexically retrieved information into a representation of multiword utterances, as well as the integration of meaning extracted from nonlinguistic modalities; this component is at the heart of the combinatorial nature of language. Finally, the *control* component relates language to action, and is invoked, for instance, when the correct target language has to be selected (in the case of bilingualism) or for handling turn taking during conversation. In principle, this MUC (memory, unification, control) framework applies to both language production and language comprehension, although details of their functional anatomy within each component will be different. The focus of this chapter is on the unification component.

Classically, psycholinguistic studies of unification have focused on syntactic analysis. However, as we saw, unification operations take place not only at the syntactic processing level. Combinatoriality is a hallmark of language across representational domains (cf. Jackendoff, 2002). Thus, also at the semantic and phonological levels, lexical elements are combined and integrated into larger structures (cf. Hagoort, 2005). In the remainder of this chapter, we will discuss semantic unification. Semantic unification refers to the integration of word meaning into an unfolding representation of the preceding context. This is more than the concatenation of individual word meanings, as is clear from the adjective-noun examples given earlier. In the interaction with the preceding sentence or discourse context, the appropriate meaning is selected or constructed, so that a coherent interpretation results.

PETER HAGOORT Donders Institute for Brain, Cognition and Behaviour, Radboud University; Max Planck Institute for Psycholinguistics, Nijmegen, The Netherlands.

ROEL M. WILLEMS Donders Institute for Brain, Cognition and Behaviour, Radboud University Nijmegen, The Netherlands.

Hereafter we will first discuss the functional characteristics of semantic unification as revealed by ERP and MEG studies. Next, results from fMRI studies will be discussed to identify the neural networks of semantic unification. In the remainder we will use the terms *unification* and *integration* interchangeably. However, in the last paragraph we propose to use the terms *integration* and *unification* for two different ways of combining information.

Functional characteristics of semantic unification

Insights into the functional characteristics of semantic unification have been especially gained through a series of event-related potential (ERP) studies. Most studies on semantic unification exploit the characteristics of the so-called N400 component in the ERP waveform. Kutas and Hillyard (1980) were the first to observe this negative-going potential with an onset at about 250 ms and a peak around 400 ms (hence the N400), whose amplitude was increased when the semantics of the eliciting word (i.e., *socks*) mismatched with the semantics of the sentence context, as in “He spread his warm bread with socks.”

Since its original discovery in 1980, much has been learned about the processing nature of the N400 (for extensive overviews, see Kutas & Federmeier, 2000; Kutas, Van Petten, & Kluender, 2006; Osterhout, Kim, & Kuperberg, 2007). In particular, as Kutas and Hillyard (1984) and many others have observed, the N400 effect does not depend on a semantic violation. For example, subtle differences in semantic expectancy, as between *mouth* and *pocket* in the sentence context “Jenny put the sweet in her mouth/pocket after the lesson,” can also modulate the N400 amplitude (Hagoort & Brown, 1994). Specifically, as the degree of semantic fit between a word and its context increases, the amplitude of the N400 decreases. This general relation between individual word meanings and the semantics of the context is independent of type of context. That is, it is found for a single-word context (Holcomb, 1993), for a sentence context (Kutas & Hillyard, 1980, 1984), and for larger discourses (van Berkum et al., 1999). Because of such subtle modulations, the N400 is generally taken to reflect processes involved in the integration of the meaning of a word into the overall semantic representation constructed for the preceding language input (Brown & Hagoort, 1993; Osterhout & Holcomb, 1992). However, different views exist as to what brings about the N400 integration effect. Federmeier and Kutas (1999; Kutas & Federmeier, 2000) proposed that in addition to its sensitivity to context, the N400 is also sensitive to the ease of accessing information from semantic memory. As such, the N400 can be seen to reflect the organization of (lexical) meaning in semantic memory. According to this view, the N400 amplitude is modulated by the degree to which the context contains retrieval cues for accessing or

selecting the stored representation for a particular word meaning. Recent evidence in favor of this position was obtained in a study by DeLong, Urbach, and Kutas (2005). These authors found an N400 effect to an indefinite article (*an* versus *a*) that excluded the semantically expected continuation, such as in “the day was breezy so the boy went out to fly an . . .,” where *kite* would be the contextually expected noun. This result suggests a contextual preactivation of the target word. However, other recent evidence is more compatible with a unification account. Li, Hagoort, and Yang (2008) investigated the neurophysiological response to manipulations of information structure. An important distinction at the level of semantic/conceptual structure is that between conceptual content and information structure. The latter refers to the division of the content of a sentence into information that is in the foreground or in the background (topic/focus; given/new). In many languages new information is accented, whereas old information is deaccented. Li and colleagues found that in Chinese the N400 to new, accented information was larger than the N400 to new, deaccented information, despite the fact that the accentuation was contextually appropriate, whereas the absence of an accent was not. The authors argue that this result is best explained by the recruitment of additional unification resources for information that is marked as more salient by accentuation.

One way to reconcile these different accounts of the N400 is by reference to different roles for the left and right hemispheres (Kutas & Federmeier, 2000; Federmeier, 2007). Federmeier and Kutas (1999) did a visual-half-field study in which participants read sentences such as “Every morning John makes himself a glass of freshly squeezed juice. He keeps his refrigerator stocked with (oranges/apples/carrots).” In this context, “oranges” is the expected continuation, “apples” is a violation but within the correct semantic category, and “carrots” is a violation that crosses the category boundary. The left-visual-field/right-hemisphere (LVF/RH) results showed a smaller N400 to oranges than to both within- and across-category violations, but no N400 difference for the two types of violation. In contrast, for the RVF/LH a reduced N400 was obtained not only for the predicted word (“orange”), but also in part for the within-category violation (“apple”) (see figure 56.1). This latter result can be explained as a consequence of a contextual prediction for the target concept. Owing to the organization of semantic memory, the within-category nontarget (“apple”) gets activated to some degree as well, resulting in a partially reduced N400. Predictive semantic processing might thus be a left-hemisphere processing mechanism, while the right-hemisphere contribution is presumably strictly postlexical in nature, only contributing to the integration of the word meaning from a lexical item that received bottom-up support on the basis of visual or acoustic input.

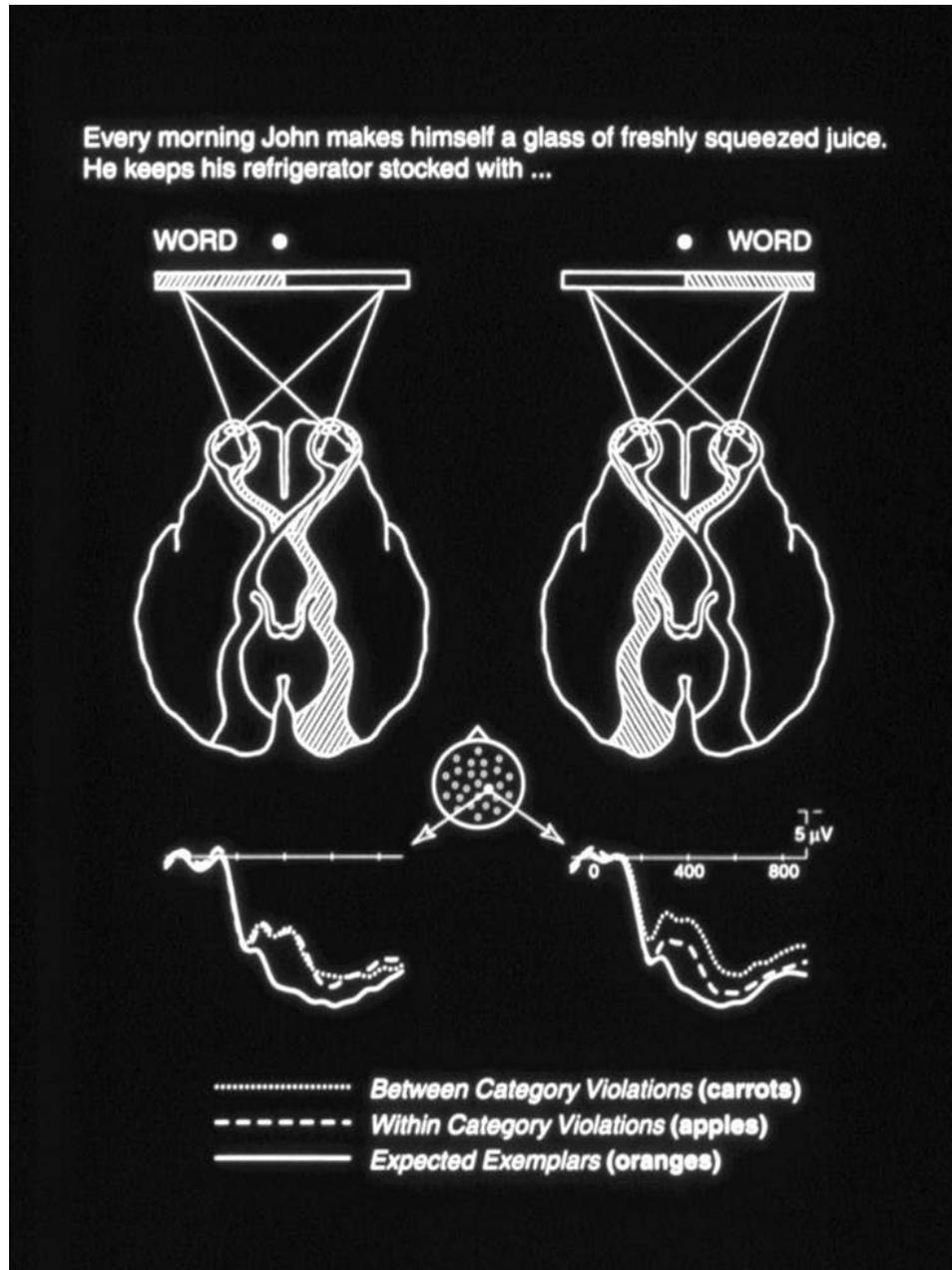


FIGURE 56.1 Participants read the sentences as in the example in a visual-half-field presentation design. Context words were presented at central fixation, whereas sentence-final target words (e.g., “oranges”) were presented to the left or right of fixation. As illustrated, words presented to the left visual field (LVF) travel initially to the right hemisphere (RH) and vice versa. ERPs are shown here from a representative (right medial central) site as indicated. The response to target words presented to the RVF (left hemisphere) (shown on right), yielded the same pattern as that observed with central fixation: expected exemplars (solid line) elicited smaller N400s than did violations of either type, but within-category violations (dashed line) also elicited smaller N400s than between-

category violations (dotted line). This pattern is indicative of a “predictive” strategy, in which semantic information associated with the expected item is preactivated in the course of processing the context information. The response to targets presented to the LVF/RH (shown on left), however, was qualitatively different: expected exemplars again elicited smaller N400s than violations, but the response to the two types of violations did not differ. This pattern is more consistent with a plausibility-based integrative strategy. Taken together, the results indicate that the hemispheres differ in how they use context to process semantic information in online language processing. (Kutas & Federmeier, 2000; reprinted with permission.)

In recent years, the N400 and other language-relevant ERP effects have been exploited to test more specific ideas about the functional characteristics of semantic unification. These include the contribution of world knowledge, the processing of silent meaning, the integration of pragmatic information, and the syntax-semantics interface. We will discuss briefly each of these theory-driven issues.

WORLD KNOWLEDGE At least since Frege (1892; see Seuren, 1998), theories of meaning make a distinction between the semantics of an expression and its truth-value in relation to our mental representation of the state of affairs in the world (Jackendoff, 2002). For instance, the sentence “Bill Clinton is the 43rd president of the USA” has a coherent semantic interpretation, but contains a proposition that is false in the light of our knowledge that George W. Bush is the 43rd president. The situation is different for the sentence “The presidential helicopter is divorced.” Under default interpretation conditions, this sentence has no coherent semantic interpretation, since the predicate “is divorced” requires an animate argument. The difference between these two sentences points to the distinction that can be made between facts of the world (“world knowledge”) and facts of the words of our language, including their meaning (“linguistic knowledge”). Hagoort, Hald, Bastiaansen, and Petersson (2004) performed a combined EEG/fMRI study that compared the unification of linguistic knowledge with the unification of world knowledge. While participants’ brain activity was recorded, they read one of three versions of a sentence such as “The Dutch trains are *yellow/white/sour* and very crowded” (critical words are in italics). It is a well-known fact among Dutch people that Dutch trains are yellow, and therefore the first version of this sentence is correctly understood as true. However, the linguistic meaning of the alternative color term *white* applies equally well to trains as the predicate *yellow*. It is world knowledge about trains in Holland that makes the second version of this sentence false. This is different for the third version, where (under standard interpretation conditions) the core semantic features of the predicate *sour* do not fit the semantic features of its argument *trains*.

Figure 56.2 presents an overview of the results. As expected, the classic N400 effect was obtained for the semantic violations. For the world-knowledge violations, a clear N400 effect was observed as well. Crucially, this effect was identical in onset and peak latency, and very similar in amplitude and topographic distribution to the semantic N400 effect. This finding is strong empirical evidence that lexical-semantic knowledge and general world knowledge are both integrated in the same time frame during sentence interpretation. The results of this world-knowledge experiment provide further evidence against an account of unification in which first the meaning of a sentence is determined, and only then is its

meaning verified in relation to our knowledge of the world. Semantic interpretation is not separate from its integration with nonlinguistic conceptual knowledge.

Further evidence in favor of an enriched composition account comes from a study on the integration of information about the speaker. In interpreting a speaker’s utterance, we take not only the preceding utterances into consideration, but also our knowledge of the speaker. For instance, we might find it odd for a man, but not for a woman of a certain age, to say, “I think I am pregnant.” At some point during language comprehension, the listener combines the information that is represented in the content of a sentence with the information she has about the speaker. The question is, When exactly does the pragmatic information about the speaker have its impact on the unfolding interpretation of the utterance? This question was answered in a recent ERP study by Van Berkum, Van den Brink, Tesink, Kos, and Hagoort (2008). Participants listened to sentences, some of which contained a specific word at which the message content became at odds with inferences about the speaker’s sex, age, and social status, as inferred from the speaker’s voice.

If voice-based inferences about the speaker are recruited by the same early unification process that combines word meanings, then speaker inconsistencies and semantic anomalies should elicit the same N400 effect. This was indeed observed. Reliable effects of speaker inconsistency were already found in the 200–300-ms latency range after word onset. The same latency effect was obtained for the straightforward semantic anomalies. These findings therefore demonstrate that sense making depends on the pragmatics of the communicative situation right from the start.

As for compositionality, the results of the studies just reviewed may mean two things, depending on one’s views on the lexicon. One possibility is that the lexicon includes declarative memory in its entirety, and then simple composition seems enough to account for the similarity between the N400 effects. Alternatively, the lexicon includes invariant (i.e., linguistic) meanings only, and then enriched composition—the thesis that the lexicon is not the only source of semantic content—seems necessary to explain the observed N400 effects (Baggio et al., in press). 4

EVENT KNOWLEDGE AND DISCOURSE MODELS Unification of lexical representations ultimately results in a discourse model—that is, a representation making what is given as input true whenever possible (recall the Dutch trains examples). Events offer a vantage point for investigating the properties of discourse models, because natural languages have very sophisticated devices for characterizing time and causation. One of these devices is aspect. This is the linguistic marking of the internal profile of events. Ferretti, Kutas, and McRae (2007) found that readers have least difficulty

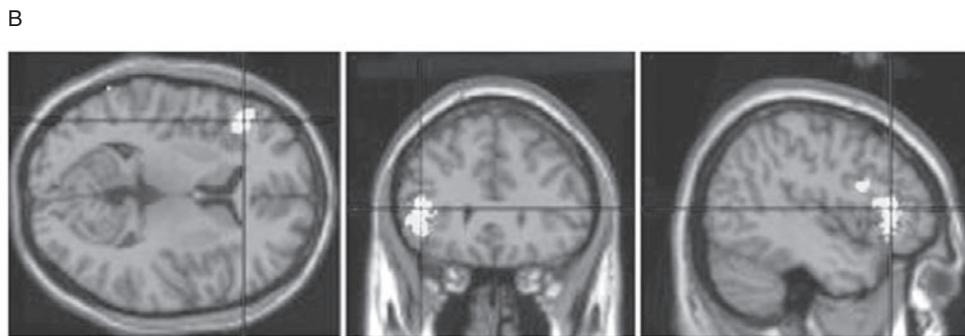
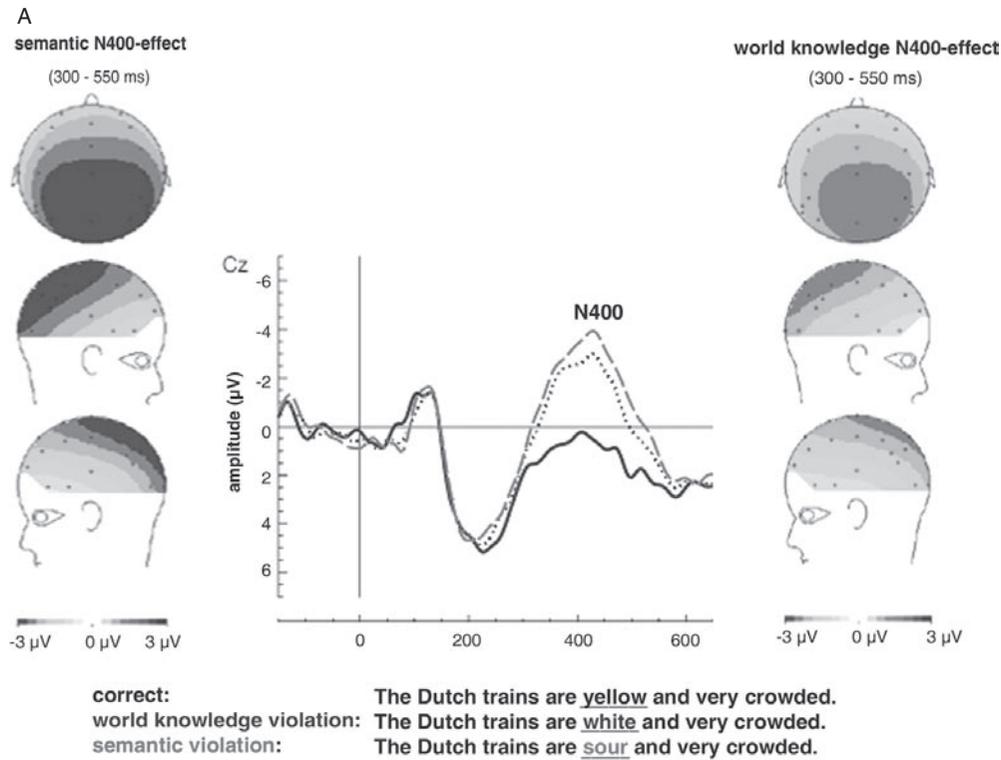


FIGURE 56.2 (A) Grand average ERPs for a representative electrode site (Cz) for correct condition (black line), world-knowledge violation (blue dotted line), and semantic violation (red dashed line). ERPs are time locked to the presentation of the critical words (underlined). Spline-interpolated isovoltage maps display the topographic distributions of the mean differences from 300 to 550 ms between semantic violation and control (left), and between world

knowledge violation and control (right). (B) The common activation for semantic and world-knowledge violations compared to the correct condition, based on the results of a minimum-T-field conjunction analysis. Both violations resulted in a single common activation ($P = 0.043$, corrected) in the left inferior frontal gyrus (in or in the vicinity of Brodmann's area 45). The crosshairs indicate the voxel of maximal activation.

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integrating locative nouns when the aspect of the main verb is imperfective and the denoted location is a prototypical one given the verb's semantics. In sentences with an imperfective, such as "The diver was snorkeling in the ocean/pond," a larger N400 was evoked by *pond* than by *ocean*. This N400 effect was reduced if the aspect was perfective, as in "The diver had snorkeled in the ocean/pond." Describing an event as ongoing using the imperfective aspect leads readers

to construct a situation model in which locations and other dimensions of the action become relevant, while such dimensions are ignored if the action is viewed perfectly.

The imperfective leads also to expectations concerning the outcome of the event described. Baggio, van Lambalgen, and Hagoort (2008) investigated whether, in sentences like "The girl was writing a letter when her friend spilled coffee on the tablecloth/paper," the goal state (a complete letter)

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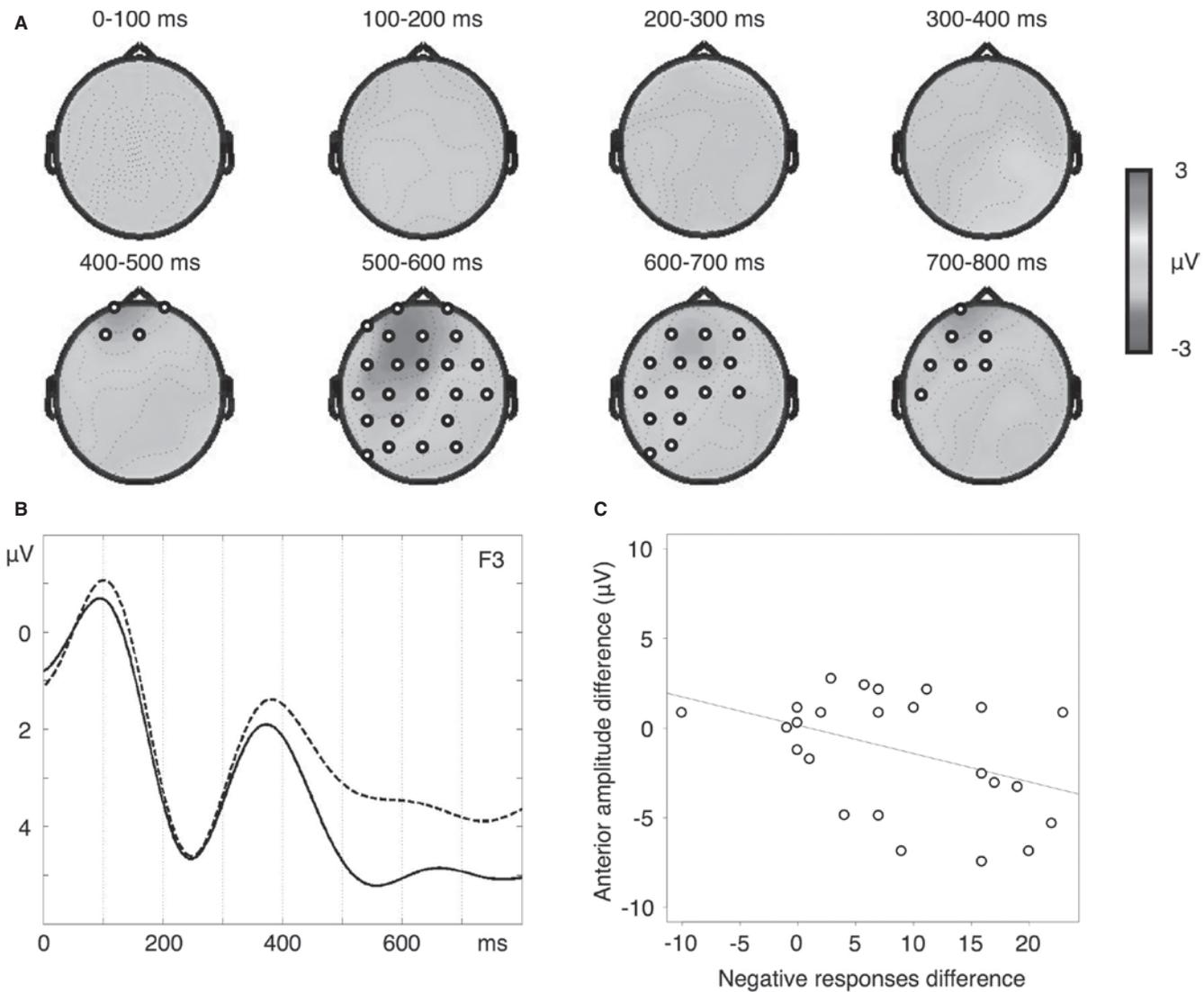
was represented online during the unification process. If the goal is predicted to occur whenever the imperfective is used, a difference should be observed at the word *paper* compared to *tablecloth*. Spilling coffee on the paper implies that the goal state was not attained, and forces the system to revise the earlier commitment to the event's completion (Baggio & van Lambalgen, 2007). Spilling coffee on the tablecloth, however, does not have this implication. *Paper* did indeed result in a larger sustained anterior negativity (SAN) compared to *tablecloth*, and the effect was correlated with the frequency with which participants concluded that the event was not completed (see figure 56.3). These results again suggest that semantic processing is not bound to asserted content, but can include inferences anticipating the outcome of actions and events, as well as other inferences invalidating previously drawn conclusions. In this sense, unification can be described as a defeasible process: discourse models built up incrementally at any one stage may have to be revised when additional information becomes available, as when the word *paper* is encountered in this example (cf. Carreiras, Garnham, Oakhill, & Cain, 1996; Sturt, 2007).

FICTIONAL DISCOURSE AND SILENT MEANING Simple composition implies that unification preserves the semantic identity of the constituent expressions. However, experimental research suggests that discourse may override even such core features of word semantics as animacy. Nieuwland and Van Berkum (2006) showed that sentences that make sense on their own, like "The peanut was salted," appear anomalous if they are embedded in a context in which the inanimate subject (the peanut) is attributed animate features. In a narrative in which the peanut danced and sang, because it fell in love with an almond it had met, the final word in "The peanut was salted" resulted in a larger N400 compared to "The peanut was in love" (see figure 56.4). This result is taken to show that discourse can override seemingly context-invariant semantic features of words.

Another interesting phenomenon is that of silent meaning—that is, meaning not expressed in the syntax and phonology of an expression. A number of linguistic devices are available to speakers and hearers that allow efficient communication of meaning beyond what is explicitly asserted. Among these are coercing expressions, functioning as a shorthand for lengthier definite descriptions, as in the classic examples "The ham sandwich in the corner wants some more coffee," where *ham sandwich* in fact refers to the person who ordered one, and "Plato is on the top shelf next to Russell," where *Plato* and *Russell* refer to copies of the works of the two philosophers. More extreme forms of coercion are possible, as in "Fishing the edges dry," where *dry* is a condensed expression for the phrase *using a dry fly*, or in resultative constructions like "Hammering the metal flat," where *flat* denotes the final state of the metal after hammer-

ing. What all these widely used expression types have in common is a silent semantic element, which has to be recovered (sometimes obligatorily) to make full sense of the sentence. Semantic processing might be taxed during such recovery process, and that is indeed what was found experimentally. Complement-coercing sentences like "The journalist began the article," which presumably means that she began writing or typing the article, are more difficult to process than sentences in which the activity is part of the asserted content like "The journalist wrote the article." The processing costs of complement coercion have been established using reading times (McElree, Traxler, Pickering, Seely, & Jackendoff, 2001), eye tracking (Traxler, Pickering, & McElree, 2002; Traxler, McElree, Williams, & Pickering, 2005), and MEG (Pylkkänen & McElree, 2007). Pylkkänen and McElree found an MEG response that was located in ventromedial prefrontal cortex to coerced sentences, which was different from the M350, the magnetic correlate of the N400. Semantic processing beyond the single-word level is therefore not restricted to processing asserted content as delivered by the input, but is crucially engaged in recovering silent meaning in presuppositions, implicatures, coercions, and so on. Crucially, recovered meanings are triggered by expressions that are given as input but are themselves phonologically and syntactically silent, an effect which shows that semantics is relatively independent from the two other components of the language system. This "autonomy of semantics" is at odds with the syntax-semantics homomorphism postulated by formal semanticists (Montague, 1970; Partee, Ter Meulen, & Wall, 1990), as well as with the "interface uniformity" upon which generative grammar is built (Culicover & Jackendoff, 2005).

UNIFICATION AND THE SYNTAX-SEMANTICS INTERFACE A language-relevant ERP effect that has been related to syntactic processing is a positivity, nowadays referred to as P600 or as P600/SPS (Coulson, King, & Kutas, 1998; Hagoort, Brown, & Osterhout, 1999; Osterhout, McLaughlin, & Bersick, 1997). The P600 is the syntactic equivalent of the N400 effect. One of the antecedent conditions of P600 effects is a violation of a syntactic constraint. The relation between N400 and the P600 effects might provide insights into the interplay between semantic and syntactic unification. Modulations of the P600 have been observed not only to syntactic violations, syntactic ambiguities, and syntactic complexity, but also to breakdowns of normal operations at the syntax-semantics interface (for a review, see Kuperberg, 2007). For example, Kim and Osterhout (2005) reported larger P600s evoked by *devouring* in "The hearty meal was devouring . . .," compared to either "The hearty meal was devoured . . ." or "The hungry boys were devouring . . ."; this despite the fact that the sentence is syntactically well



Het meisje was een brief aan het schrijven toen haar vriendin koffie op het tafelkleed morste.

'The girl was writing a letter when her friend spilled coffee on the tablecloth.'

Het meisje was een brief aan het schrijven toen haar vriendin koffie op het papier morste.

'The girl was writing a letter when her friend spilled coffee on the paper.'

FIGURE 56.3 (A) Grand-average topographies displaying the mean amplitude difference between the ERPs evoked by the sentence-final verb when it terminated versus when it did not terminate the accomplishments in the progressive. Circles represent electrodes in a significant ($P < 0.05$) cluster. (B) Grand-average ERP waveforms from a representative site (F3) time-locked to the onset (0 ms) of the verb in terminated versus nonterminated accomplishments. Negative values are plotted upward. (C) Scatter plot displaying the correlation between the amplitude of the sustained

anterior negativity elicited by terminated accomplishments and the frequency of negative responses in a button-press, probe-selection task ($r = -0.415$, $T(22) = -2.140$, $P = 0.043$). The mean difference of negative responses between terminated and nonterminated accomplishments is plotted on the abscissa. The mean amplitude difference at frontopolar and frontal electrodes between terminated and nonterminated accomplishments in the 500–700-ms interval following the onset of the sentence-final verb is plotted on the ordinate.

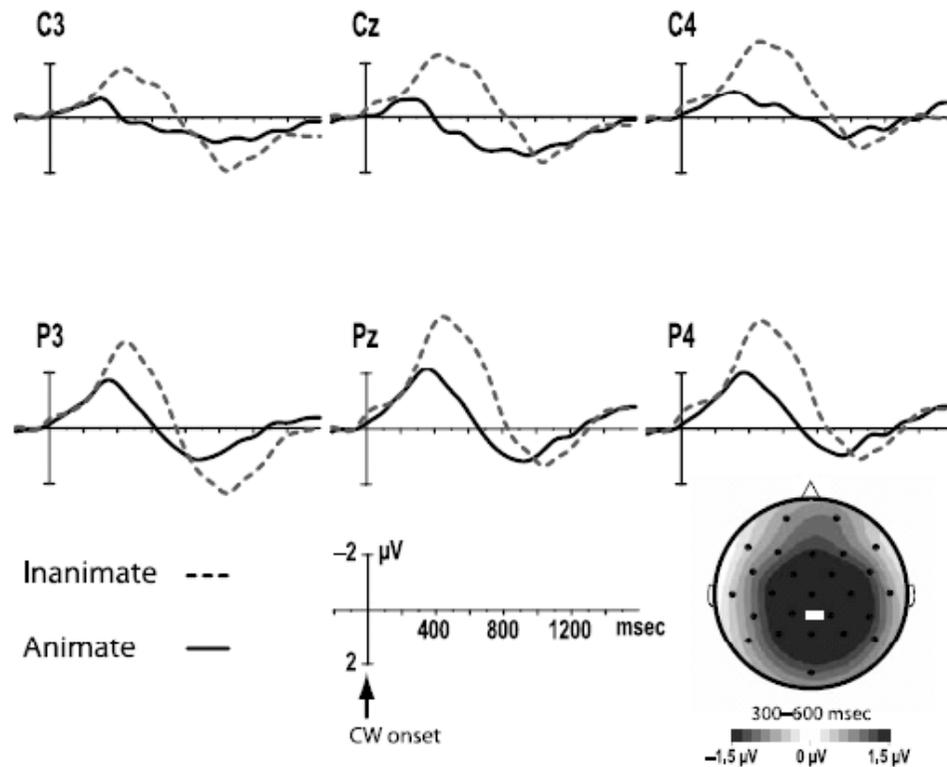


FIGURE 56.4 N400 effects triggered by a correct predicate (*salted*) that is, however, contextually disfavored in comparison to an incorrect predicate (*in love*). Waveforms are presented for representative

electrode sites, time-locked to the onset of the critical inanimate/animate predicate in the fifth sentence. (After Nieuwland & Van Berkum, 2006.)

formed (see figure 56.5). The semantics of *meal* and *devour* suggest a plausible thematic role assignment to *meal*: a *theme* instead of an *agent* as the syntax implies. In this case, semantic plausibility overrides syntactic constraints, and the verb *devouring* is presumably perceived as a morphosyntactic violation indexed by the P600. Conflicts between syntactic and semantic constraints might result in N400 or P600 effects depending on whether, respectively, the semantic or the syntactic constraints are the weakest. In cases where the input is anomalous because of a conflict between semantic and syntactic cues, the *modus operandi* of the system seems to obey a “loser takes all” principle. That is, if the semantic cues are stronger than the syntactic cues, the effect will appear at the level of syntactic unification (P600). Kuperberg (2007) argues that there are at least two neural routes subserving language comprehension: (1) a semantic, memory-based stream that provides elementary meanings as well as conceptual, categorical, and thematic relations between them; (2) a combinatorial stream that provides analyses based on morphosyntactic constraints and thematic roles as given in the input. The P600 reported by Kim and Osterhout (2005), for example, might be taken to suggest that semantic associations between words are the strongest constraints—for instance, because in this case they are taken into account earlier than the syntactic cues.

CONCLUSION In general, ERP research on semantic processing has found that word meaning is very rapidly assembled into compound meaning. This statement holds for individual word meanings in the context of single words, sentences, or discourse. But it also holds for meaning that is extracted from pictures, co-speech gestures, or stereotypes inferred from speaker characteristics (Willems, Özyürek, & Hagoort, 2007, 2008; Van Berkum et al., 2008). The effects of semantic processing are most often observed as modulations of the N40 amplitude. The topographic distribution of the N400 differs slightly for different stimulus types. It is more evenly distributed for auditory than for the visual N400. Pictures and co-speech gestures elicit a more frontal N400 than sentences without concomitant nonlinguistic information. This finding suggests that the set of neural generators contributing to the scalp-recorded N400 is not fully overlapping for the different types of meaningful stimuli. This result is consistent with the results from fMRI studies, showing both overlapping and distinct activations in connection to the various types of meaningful input (see the next section). Intracranial recordings and MEG studies indicate that the scalp-recorded N400 is caused by coordinated activity in a number of different brain areas, including the anterior inferotemporal cortex (McCarthy, Nobre, Bentin, & Spencer, 1995), the superior temporal cortex (Dale et al.,

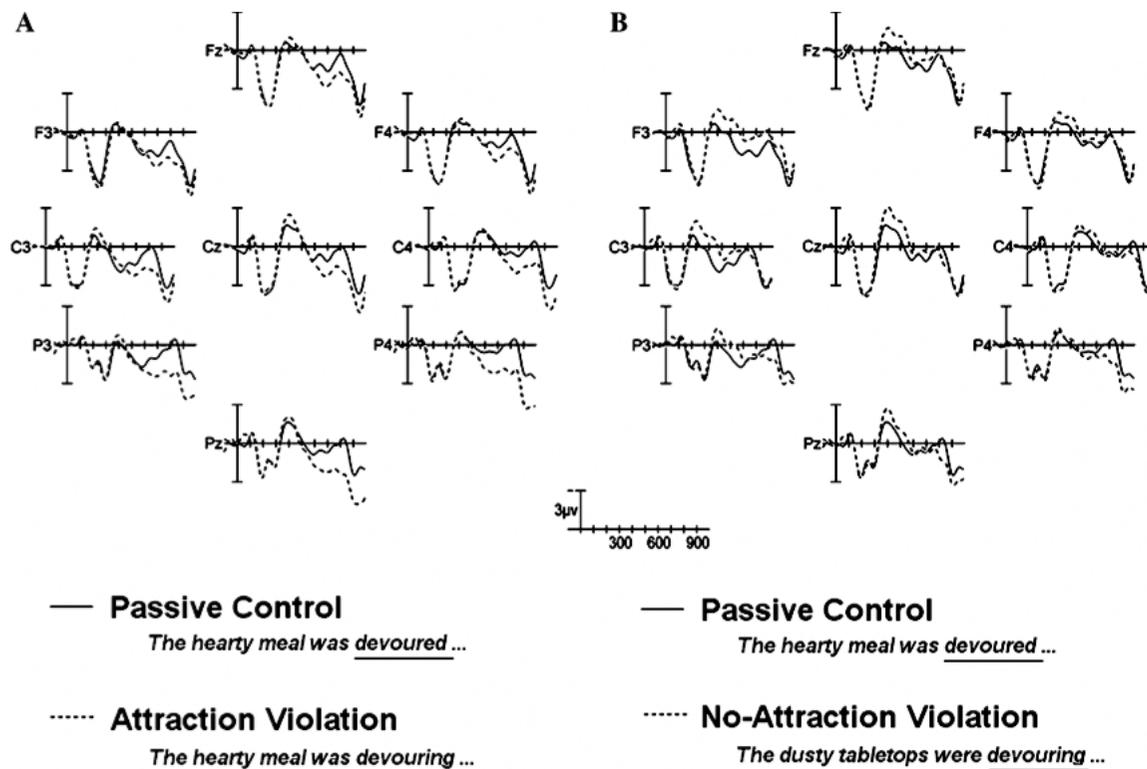


FIGURE 56.5 At the interface between syntax and semantics. Grand-average ERPs recorded at three midline sites and six medial-lateral sites. All sentences are syntactically correct. (A) ERPs to passive control verbs (solid line) and thematic violation verbs (dashed line). (B) ERPs to active control verbs (solid line) and thematic viola-

tion verbs (dashed line). In both cases the inconsistency between grammatical roles and thematic role biases resulted in robust P600 effects. Onset of the critical verbs is indicated by the vertical bar. Each hash mark represents 100 ms. Positive voltage is plotted down. (Kim & Osterhout, 2005; reprinted with permission.)

2000; Helenius, Salmelin, Service, & Connolly, 1998; Halgren et al., 2002), and the left inferior frontal cortex (Halgren et al., 1994, 2002; Guillem, Rougier, & Claverie, 1999). Other ERP effects (e.g., anterior negativities) have also been observed to aspects of postlexical semantic processing. How they differ from the N400 effects in their functional characterization is an issue for further research.

The semantic unification network

In recent years a series of fMRI studies were aimed at identifying the semantic unification network. These studies either compared sentences containing semantic/pragmatic anomalies with their correct counterparts (Hagoort et al., 2004; Newman, Pancheva, Ozawa, Neville, & Ullman, 2001; Kuperberg et al., 2000, 2003; Kuperberg, Sitnikova, & Lakshmanan, 2008; Ni et al., 2000; Baumgaertner, Weiller, & Buchel, 2002; Kiehl, Laurens, & Liddle, 2002; Friederici, Ruschemeyer, Hahne, & Fiebach, 2003; Ruschemeyer, Zysset, & Friederici, 2006) or compared sentences with and without semantic ambiguities (Hoening & Scheef, 2005; Rodd, Davis, & Johnsrude, 2005; Zemleni, Renken, Hoeks, Hoogduin, & Stowe, 2007; Davis et al., 2007). The most

consistent finding across all these studies is the activation of the left inferior frontal cortex (LIFC), more particularly BA 47 and BA 45. In addition, the left superior and middle temporal cortex is often found to be activated (see figure 56.6 for an overview), as well as left inferior parietal cortex. For instance, Rodd and colleagues had subjects listen to English sentences such as “There were dates and pears in the fruit bowl” and compared the BOLD response of these sentences to the BOLD response of sentences such as “There was beer and cider on the kitchen shelf.” The crucial difference between these sentences is that the former contains two homophones—“dates” and “pears”—which, when presented auditorily, have more than one meaning. This is not the case for the words in the second sentence. The sentences with the lexical ambiguities led to increased activations in LIFC and in the left posterior middle/inferior temporal gyrus. In this experiment all materials were well-formed English sentences in which the ambiguity usually goes unnoticed. Nevertheless, the results were very similar to those obtained in experiments that used semantic anomalies. Areas involved in semantic unification were found to be sensitive to the increase in semantic unification load that resulted from the ambiguous words.

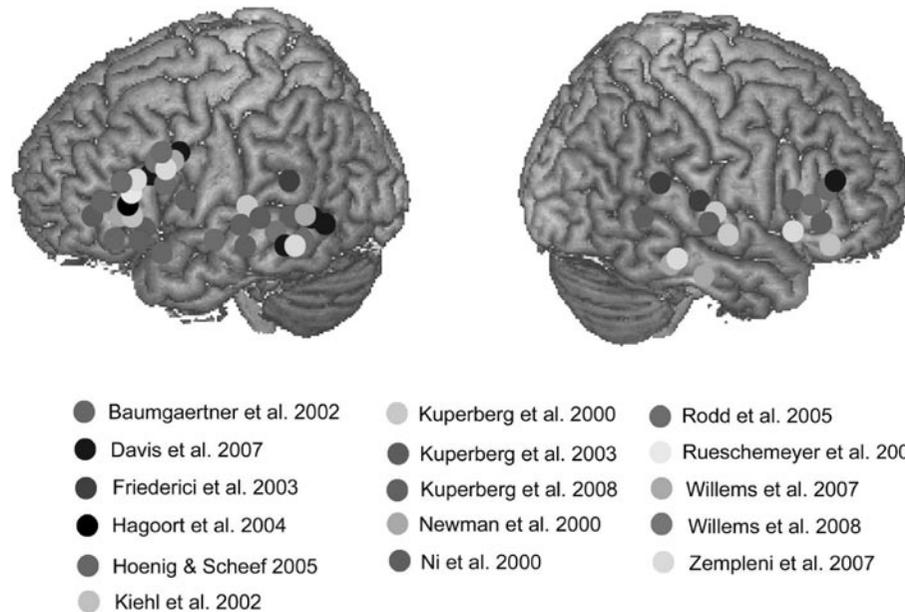


FIGURE 56.6 Overview of local maxima in inferior frontal cortex and in temporal cortex in neuroimaging studies employing sentences with semantic anomalies or semantic ambiguities. The local maxima (in MNI space) of each study were overlaid on a rendering of a brain in MNI space. For local maxima see tables 56.1 and 56.2; for a summary of the results see table 56.3. Rendering was

made using MRICroN. Please note that the local maxima of the Ni and colleagues (2000) and the Kuperberg and colleagues (2003) studies are displayed, but that these are not based on coordinates, since no coordinates were provided. The local maxima are drawn by hand based upon the figures in the respective papers.

In short, the semantic unification network seems to include at least LIFC, left superior/middle temporal cortex, and the (left) inferior parietal cortex. To some degree, the right hemisphere homologues of these areas are also found to be activated (see figure 56.6). In the following subsections we will discuss the possible contributions of these regions to semantic unification.

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THE MULTIMODAL NATURE OF SEMANTIC UNIFICATION
 An indication for the respective functional roles of the left frontal and temporal cortices in semantic unification comes from a few studies investigating semantic unification of multimodal information with language. Using fMRI, Willems and colleagues assessed the neural integration of semantic information from spoken words and from co-speech gestures into a preceding sentence context (Willems et al., 2007). Spoken sentences were presented in which a critical word was accompanied by a co-speech gesture. Either the word or the gesture could be semantically incongruous with respect to the previous sentence context. Both an incongruous word and an incongruous gesture led to increased activation in LIFC as compared to congruous words and gestures (see Willems et al., 2008, for a similar finding with pictures of objects). Interestingly, the activation of the left posterior STS was increased by an incongruous spoken word but not by an incongruous hand gesture. The latter resulted in a specific increase in dorsal premotor cortex

(Willems et al., 2007). This finding suggests that activation increases in left posterior temporal cortex are triggered most strongly by processes involving the retrieval of lexical-semantic information. LIFC, however, is a key node in the semantic unification network, unifying semantic information from different modalities.

From these findings it seems that semantic unification is realized in a dynamic interplay between LIFC as a multimodal unification site on the one hand, and modality-specific areas on the other hand.

SEMANTIC UNIFICATION BEYOND THE SENTENCE LEVEL
 Recently a few studies have set out to investigate the neural networks involved in semantic processing at the level of multisentence utterances, such as short stories. Besides the network that is also activated to semantic unification at the sentence level, story comprehension involves activation of dorsomedial prefrontal cortex and, presumably, right inferior frontal cortex. In a recent meta-analysis, Ferstl and colleagues report the consistent involvement of medial prefrontal cortex, left STS/MTG, and LIFC when participants process coherent text as compared to sentences that do not form a coherent story or as compared to word lists (Ferstl, Neumann, Bogler, & von Cramon, 2008). In a variant of this line of research, Kuperberg, Lakshmanan, Caplan, and Holcomb (2006) presented participants with sentence quartets in which the relation of the last

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TABLE 56.1

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Involvement of the inferior frontal cortex in fMRI studies of sentence comprehension employing semantic anomalies or semantic ambiguities.

The table shows the studies that were used for the overview in figure 56.6, a brief description of the contrast that was employed in each of the studies, the reported coordinates of the local maxima in inferior frontal cortex in MNI space, and a verbal description of the location of the local maxima. When necessary, Talairach coordinates were converted to MNI space using the transformation suggested by Brett (<http://imaging.mrc-cbu.cam.ac.uk/imaging/MniTalairach>). Note that in computing the mean coordinates the findings from Kuperberg and colleagues (2003) and Ni and colleagues (2000) were not taken into consideration, since no coordinates were reported in these studies.

Study	Comparison	Coordinates <i>x y z</i> (MNI)	Region
Baumgaertner et al., 2002	Sem. incongruent > congruent	-51 36 -6	Left IFG
Davis et al., 2007	High ambiguity > low ambiguity	-40 24 18 -48 6 34 -40 18 24 46 36 18	Left IFG Right IFG
Friederici et al., 2003	Sem. incongruent > congruent	No activation	—
Hagoort et al., 2004	Sem. incongruent > congruent \cap World knowledge incongruent > congruent	-44 30 8	Left IFG
Hoening & Scheef, 2005	Sem. incongruent > congruent	-50 18 -14 -50 43 11	Left IFG
Kiehl et al., 2002	Sem. incongruent > congruent	-48 32 4 36 32 -16	Left IFG/ant. temporal Right IFG/ant. temporal
Kuperberg et al., 2000	Sem. incongruent > congruent	No activation	—
	Pragm. incongruent > congruent	No activation	—
Kuperberg et al., 2003	Pragm. incongruent > congruent	(No coordinates)	Left IFG
Kuperberg et al., 2008	Pragmatic incongruent > congruent	-43 25 -10	Left IFG
	Sem. incongruent > congruent	-49 4 10 29 19 5	Left IFG Right IFG
Newman et al., 2001	Sem. incongruent > congruent	-50 34 5	Left IFG
Ni et al., 2000	Sem. incongruence detection > tone pitch discrimination	(No coordinates)	Left IFG
	Oddball paradigm with semantically incongruent sentences	(No coordinates)	Right IFG Left IFG
Rodd et al., 2005	High ambiguity > low ambiguity	(No coordinates) -50 30 20 -56 16 22 -42 14 32 36 26 4 50 36 16	Right IFG Left IFG Left IFS Right IFG Right IFG
Rueschemeyer et al., 2006	Sem. incongruent > synt. incongruent	-50 30 15	Left ant. IFG
Willems et al., 2007	Sem. incongruent > congruent	-43 11 27	Left IFS
Willems et al., 2008	Sem. incongruent > congruent	-45 14 27	Left IFS
Zempleni et al., 2007	Subordinate meaning > dominant meaning	-48 26 20 -52 16 26 34 20 -10	Left IFG Left IFG Right IFG

TABLE 56.2

Involvement of the temporal cortex in fMRI studies of sentence comprehension employing semantic anomalies or semantic ambiguities.

The table shows the studies that were used for the overview in figure 56.6, a brief description of the contrast that was employed in each of the studies, the reported coordinates of the local maxima in temporal cortex in MNI space, and a verbal description of the location of the local maxima. When necessary, Talairach coordinates were converted to MNI space using the transformation suggested by Brett (<http://imaging.mrc-cbu.cam.ac.uk/imaging/MniTalairach>). Note that in computing the mean coordinates the findings from Kuperberg and colleagues (2003) and Ni and colleagues (2000) were not taken into consideration, since no coordinates were reported in these studies.

Study	Comparison	Coordinates <i>x y z</i> (MNI)	Region
Baumgaertner et al., 2002	Sem. incongruent > congruent	No activation	—
Davis et al., 2007	High ambiguity > low ambiguity	-50 -44 -12 -54 -60 -2	Left ITG
Friederici et al., 2003	Sem. incongruent > congruent	-60 -42 20 63 -40 20 58 -24 13	Left STG Right STG Right STG
Hagoort et al., 2004	Sem. incongruent > congruent	No activation	—
Hoening & Scheef, 2005	Sem. incongruent > congruent	No activation	—
Kiehl et al., 2002	Sem. incongruent > congruent	No activation	—
Kuperberg et al., 2000	Sem. incongruent > congruent	43 -11 -7 49 -17 4	Right MTG Right STG
Kuperberg et al., 2003	Pragm. incongruent > congruent	-49 -31 9	Left STG
Kuperberg et al., 2008	Pragm. incongruent > congruent	(No coordinates)	Left STS
	Pragmatic violations > correct sentences	-27 -28 -19	Left ant. med. temporal cortex
	Sem. incongruent > congruent	-53 -20 -1 58 -19 3	Left STG Right STG
Newman et al., 2001	Sem. incongruent > congruent	70 -36 -15	Right MTG
Ni et al., 2000	Sem. incongruence detection > tone pitch discrimination	(No coordinates)	Left STG/MTG
	Oddball paradigm with semantically incongruent sentences	(No coordinates)	Right STG/MTG Left pSTG
Rodd et al., 2005	High ambiguity > low ambiguity	-52 -50 -10 -58 -8 -6	Left pITG Left STG
Rueschemeyer et al., 2006	Sem. incongruent > synt. incongruent	—	—
Willems et al., 2007	Sem. incongruent > congruent	-53 -52 2	Left STS
Willems et al., 2008	Sem. incongruent > congruent	-53 -35 -3	Left STS
Zempleni et al., 2007	Subordinate meaning > dominant meaning	-50 -48 -12 56 -34 -16	Left ITG/MTG Right ITG/MTG

TABLE 56.3

Summary of the activations in the studies used for the overview in figure 56.6.

The coordinates from tables 56.1 and 56.2 were used. Table 56.3 specifies the mean coordinates for left and right inferior frontal and temporal cortices, the standard deviation in the x , y , and z directions in millimeters, the mean Euclidian distance of the local maxima to the mean coordinates, the number of maxima that were reported, and the number of studies that report maxima in that region. Note that the number of maxima is higher than the number of studies, since several studies report more than one maximum. Note that the findings from Kuperberg and colleagues (2003) and Ni and colleagues (2000) were not used in computing the mean coordinates, since no coordinates were reported in these studies.

	Mean ($x\ y\ z$) (MNI)	SD ($x\ y\ z$) (mm)	Mean Distance to Mean (mm)	Number of Studies (out of total)
<i>Inferior frontal cortex</i>				
Left	-47 22 14	4.3 10.6 13.9	16.3	14/16
Right	39 28 3	7.9 7.7 13.6	15.0	6/16
<i>Temporal cortex</i>				
Left	-51 -38 -3	8.6 15.4 10.9	18.0	10/16
Right	57 -26 0	8.8 10.9 13.7	17.2	6/16

sentence to the previous story context was manipulated. The less related sentences required an extra causal inference in order to make sense of the story. It was found that less related sentences (which evoked more inferencing) led to stronger activations in left and right IFC, left MTG, left middle frontal gyrus, and bilateral medial prefrontal cortex (Kuperberg et al.; see Hasson, Nusbaum, & Small, 2007, for a related result). These and other studies (e.g., St George, Kutas, Martinez, & Sereno, 1999; Xu, Kemeny, Park, Frattali, & Braun, 2005; Sieborger, Ferstl, & von Cramon, 2007) suggest that LIFC and left superior/middle temporal cortex are also important for unification of information beyond the sentence level. It is interesting to note that the medial prefrontal cortex, which is found activated for discourse but not for sentence-level processing, has been implicated in so-called mentalizing tasks, requiring the observer to take the perspective of someone else (Buckner, Andrews-Hanna, & Schacter, 2008; Frith & Frith, 2006). According to Mason and Just, this domain-general area is recruited in discourse processing for the sake of interpreting a protagonist's or agent's perspective (Mason & Just, 2006). In addition, right-hemisphere regions are sometimes but not consistently reported in the context of discourse processing (Maguire, Frith, & Morris, 1999; St George et al.; Ferstl et al.; Martin-Loeches et al., 2008; see Ferstl et al.; Mason & Just, 2006, for extensive reviews). Some studies find that the temporal poles may be related to successful integration during story comprehension (Fletcher et al., 1995; Maguire et al.). The studies that report these activations are mostly done using PET. It is hard to assess the consistency of temporal pole activation during story/text comprehension because of the susceptibility to artifacts that these regions often suffer from in fMRI studies (but see Xu et al.; Ferstl et al.).

CONTROLLED PROCESSING AND SELECTION ACCOUNTS FOR LIFC Although LIFC (including Broca's area) has traditionally been construed as a language area, there is a wealth of recent neuroimaging data suggesting that its role extends beyond the language domain. Several authors have therefore argued that LIFC function is best characterized as "controlled retrieval" or "(semantic) selection" (Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997; Wagner, Pare-Blagoev, Clark, & Poldrack, 2001; Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005; Gold, Balota, Kirchoff, & Buckner, 2005; Moss et al., 2005; Thompson-Schill, Bedny, & Goldberg, 2005). For instance, Thompson-Schill and colleagues showed that LIFC was more strongly activated in a verb-generation task when the noun that served as the cue allowed for many different verb responses, as opposed to nouns that are reliably related to only one or a few verbs (Thompson-Schill et al., 1997). In response to the noun cue "scissors," for example, most participants generate the verb "to cut," whereas the noun "wheel" triggers a more diverse set of responses. On the basis of these and other findings, it was argued that LIFC guides semantic selection among competing alternatives, with higher activation when there are more competitors.

How does the selection account of LIFC function relate to the unification account? As is discussed in more detail elsewhere, unification often implies selection (Hagoort, 2005). For instance, in the study by Rodd and colleagues described earlier, increased activation in LIFC is most likely due to increased selection demands in reaction to sentences with ambiguous words. Selection is often, but not always, a prerequisite for unification. Unification with or without selection is a core feature of language processing. During natural language comprehension, information has to be kept in working memory for a certain period of time, and incoming

information has to be integrated and combined with previous information. The combinatorial nature of language necessitates that a representation be constructed online, without the availability of an existing representation of the utterance in long-term memory. In addition, some information sources that are integrated with language do not have a stable representation in long-term memory such that they can be selected. For instance, there is no stable representation of the meaning of co-speech gestures, which are highly ambiguous outside of a language context. Still, in all these cases increased activation is observed in LIFC, such as when the integration load of information from co-speech gestures is high (Willems et al., 2007). Similarly, it is unlikely that integration of information about characteristics of the speaker as indicated by the acoustics of the voice (e.g., whether the speaker is male or female, child or adult) relies on selection. Nevertheless, increased activation levels are observed in LIFC when integrating speaker characteristics with the content of the message gets more difficult (Tesink et al., accepted). Therefore, unification is a more general account of LIFC function. It implies selection, but it covers additional integration processes as well.

INTEGRATION VERSUS UNIFICATION We have so far used the term “unification” to refer to the assembly of complex meaning. Although the term “integration” is often used as a synonym for unification, including by ourselves, we suggest that it is useful to make a functional distinction between the two. Semantic integration is at stake if different sources of information converge on a common memory representation. An example is the sound and the sight of an animal (e.g., a barking dog). The sight of a dog, the barking sound, and their combined occurrence most likely all activate a memory representation of “dog” that has multimodal characteristics. Semantic unification, however, is always a constructive process in which a semantic representation is constructed that is not already available in memory. This distinction makes opposite predictions for the BOLD response. Semantic unification is always harder for semantic incongruities. These should result in a stronger BOLD response than semantically congruent items. In contrast, congruent input results in converging support for a prestored representation, which might thus be more strongly activated compared to a situation with incongruent input. Hence, in the case of integration the congruent condition will elicit a stronger BOLD response than the incongruent condition. A few studies on multimodal integration have indeed reported activation increases to matching stimulus combinations. For instance, Van Atteveldt, Formisano, Goebel, and Blomert (2004) observed a higher activation level in left superior temporal cortex in response to a matching phoneme and letter combination (e.g., letter “p” with phoneme [p]) as compared to a mismatching combination (e.g., letter “k”

with phoneme [p]) (see also Calvert, Campbell, & Brammer, 2000, for the integration of lip movements and speech sounds). The same is true in the study by Beauchamp, Lee, Argall, and Martin (2004), who found higher activation in left posterior temporal cortex to the matching combination of a picture of an object and its sound versus an incongruent combination. In a recent paper Hein and colleagues (2007) reported an interesting difference between inferior frontal cortex (IFC) and posterior temporal cortex. The IFC showed a stronger response to incongruent familiar animal sounds and images (e.g., a meowing dog) than to the familiar combination (a barking dog). This was, however, not observed in STG and pSTS. This region was found to be more strongly activated to highly familiar combinations of objects and sounds as compared to combinations of artificial objects and sounds. This result suggests a possible division of labor between inferior frontal and superior temporal areas, with a stronger contribution to integration for temporal cortex and a stronger role for the IFC in unification—that is, in constructing a common representation that is not already available in long-term memory.

However, as we have seen, many studies on sentence processing have found increased activation, especially in left superior/middle temporal cortex when the (semantic) unification load of a word increases given the preceding sentence context (e.g., Bookheimer, 2002; Friederici et al., 2003; Kuperberg et al., 2003; Hagoort et al., 2004; Rodd et al., 2005; Ruschemeyer, Fiebach, Kempe, & Friederici, 2005; Davis et al., 2007; Willems et al., 2007, 2008). We propose that this results from signals from LIFC, indicating that in the service of unification, lexical-semantic information needs to be maintained active longer or needs to be reaccessed when unification load increases (cf. Humphries, Binder, Medler, & Liebenthal, 2007). In this way, it is the dynamic interplay between LIFC and left superior/middle temporal cortex that is necessary for successful semantic unification.

Conclusion

Over and above the retrieval of individual word meanings, sentence and discourse processing requires combinatorial operations that result in a coherent interpretation of multiword utterances. These operations do not adhere to a simple principle of compositionality. World knowledge, information about the speaker, co-occurring visual input, and discourse information all trigger electrophysiological responses similar to those triggered by sentence-internal semantic information. A network of brain areas, including the left inferior frontal gyrus, the left superior/middle temporal cortex, the left inferior parietal cortex, and, to a lesser extent, their right-hemisphere homologues are recruited to perform semantic unification. In line with the MUC framework,

semantic unification operations are under top-down control of left, and in the case of discourse, also right inferior frontal cortex. This contribution modulates activations of lexical information in memory as represented by the left superior and middle temporal cortex, presumably with additional support for unification operations in left inferior parietal areas (e.g., angular gyrus). A more precise account of the individual contributions of these core nodes in the unification network awaits further research.

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REFERENCES

- BADRE, D., POLDRACK, R. A., PARE-BLAGOEV, E. J., INSLER, R. Z., & WAGNER, A. D. (2005). Dissociable controlled retrieval and generalized selection mechanisms in ventrolateral prefrontal cortex. *Neuron*, *47*, 907–918.
- BAGGIO, G., & VAN LAMBALGEN, M. (2007). The processing consequences of the imperfective paradox. *J. Semantics*, *24*, 307–330.
- BAGGIO, G., VAN LAMBALGEN, M., & HAGOORT, P. (2008). Computing and recomputing discourse models: An ERP study. *J. Mem. Lang.*, *59*, 36–53.
- 13 BAGGIO, G., VAN LAMBALGEN, M., & HAGOORT, P. (in press). The processing consequences of compositionality. In W. Hinzen, E. Machery, & M. Werning (Eds.), *The Oxford handbook of compositionality*. Oxford, UK: Oxford University Press.
- BAUMGAERTNER, C., WEILLER, C., & BUCHEL, C. (2002). Event-related fMRI reveals cortical sites involved in contextual sentence integration. *Neuroimage*, *16*, 736–745.
- BEAUCHAMP, M. S., LEE, K. E., ARGALL, B. D., & MARTIN, A. (2004). Integration of auditory and visual information about objects in superior temporal sulcus. *Neuron*, *41*, 809–823.
- BOOKHEIMER, S. (2002). Functional MRI of language: New approaches to understanding the cortical organization of semantic processing. *Ann. Rev. Neurosci.*, *25*, 151–188.
- BROWN, C., & HAGOORT, P. (1993). The processing nature of the N400: Evidence from masked priming. *J. Cogn. Neurosci.*, *5*, 34–44.
- BUCKNER, R. L., ANDREWS-HANNA, J. R., & SCHACTER, D. L. (2008). The brain's default network: Anatomy, function, and relevance to disease. *Ann. NY Acad. Sci.*, *1124*, 1–38.
- CALVERT, G. A., CAMPBELL, R., & BRAMMER, M. J. (2000). Evidence from functional magnetic resonance imaging of crossmodal binding in the human heteromodal cortex. *Curr. Bio.*, *10*, 649–657.
- CARREIRAS, M., GARNHAM, A., OAKHILL, J., & CAIN, K. (1996). The use of stereotypical gender information in constructing a mental model: Evidence from English and Spanish. *Q. J. Exp. Psychol. [A]*, *49*, 639–663.
- COULSON, S., KING, J. W., & KUTAS, M. (1998). Expect the unexpected: Event-related brain response to morphosyntactic violations. *Lang. Cogn. Process.*, *13*, 21–58.
- CULICOVER, P., & JACKENDOFF, R. (2005). *Simpler syntax*. Oxford, UK: Oxford University Press.
- CUTLER, A., & CLIFTON, C. E. (1999). Comprehending spoken language: A blueprint of the listener. In C. M. Brown and P. Hagoort (Eds.), *The neurocognition of language* (pp. 123–166). Oxford, UK: Oxford University Press.
- DALE, A. M., LIU, A. K., FISCHL, B. R., BUCKNER, R. L., BELLIVEAU, J. W., LEWINE, J. D., & HALGREN, E. (2000). Dynamic statistical parametric mapping: Combining fMRI and MEG for high-resolution imaging of cortical activity. *Neuron*, *26*, 55–67.
- DAVIS, M. H., COLEMAN, M. R., ABSALOM, A. R., RODD, J. M., JOHNSRUDE, I. S., MATTA, B. F., OWEN, A. M., & MENON, D. K. (2007). Dissociating speech perception and comprehension at reduced levels of awareness. *Proc. Natl. Acad. Sci. USA*, *104*, 16032–16037.
- DELONG, K. A., URBACH, T. P., & KUTAS, M. (2005). Probabilistic word pre-activation during language comprehension inferred from electrical brain activity. *Nat. Neurosci.*, *8*, 1117–1121.
- FEDERMEIER, K. D. (2007). Thinking ahead: The role and roots of prediction in language comprehension. *Psychophysiology*, *44*, 491–505.
- FEDERMEIER, K. D., & KUTAS, M. (1999). A rose by any other name: Long-term memory structure and sentence processing. *J. Mem. Lang.*, *41*, 469–495.
- FERRETTI, T. R., KUTAS, M., & McRAE, K. (2007). Verb aspect and the activation of event knowledge. *J. Exp. Psychol. Learn. Mem. Cogn.*, *33*, 182–196.
- FERSTL, E. C., NEUMANN, J., BOGLER, C., & VON CRAMON, D. Y. (2008). The extended language network: A meta-analysis of neuroimaging studies on text comprehension. *Hum. Brain Mapp.*, *29*, 581–593.
- FLETCHER, P. C., HAPPE, F., FRITH, U., BAKER, S. C., DOLAN, R. J., FRACKOWIAK, R. S., & FRITH, C. D. (1995). Other minds in the brain: A functional imaging study of “theory of mind” in story comprehension. *Cognition*, *57*, 109–128.
- FODOR, J., & LEPORE, E. (2002). *The compositionality papers*. Oxford, UK: Oxford University Press.
- FREGE, G. (1892). Über Sinn und Bedeutung. *Zeitschrift für Philosophie und philosophische Kritik*, *100*, 25–50.
- FRIEDERICI, A. D., RUSCHEMEYER, S. A., HAHNE, A., & FIEBACH, C. J. (2003). The role of left inferior frontal and superior temporal cortex in sentence comprehension: Localizing syntactic and semantic processes. *Cereb. Cortex*, *13*, 170–177.
- FRITH, C. D., & FRITH, U. (2006). The neural basis of mentalizing. *Neuron*, *50*, 531–534.
- GOLD, B. T., BALOTA, D. A., KIRCHHOFF, B. A., & BUCKNER, R. L. (2005). Common and dissociable activation patterns associated with controlled semantic and phonological processing: Evidence from fMRI adaptation. *Cereb. Cortex*, *15*, 1438–1450.
- GUILLEM, F., ROUGIER, A., & CLAVERIE, B. (1999). Short- and long-delay intracranial ERP repetition effects dissociate memory systems in the human brain. *J. Cogn. Neurosci.*, *11*, 437–458.
- HAGOORT, P. (2005). On Broca, brain, and binding: A new framework. *Trends Cogn. Sci.*, *9*, 416–423.
- HAGOORT, P., & BROWN, C. (1994). Brain responses to lexical ambiguity resolution and parsing. In C. Clifton, Jr., L. Frazier, & K. Rayner (Eds.), *Perspectives on sentence processing* (pp. 45–81). Hillsdale, NJ: Lawrence Erlbaum.
- HAGOORT, P., BROWN, C., & OSTERHOUT, L. (1999). The neurocognition of syntactic processing. In C. M. Brown and P. Hagoort (Eds.), *The neurocognition of language* (pp. 273–317). Oxford, UK: Oxford University Press.
- HAGOORT, P., HALD, L., BASTIAANSEN, M., & PETERSSON, K. M. (2004). Integration of word meaning and world knowledge in language comprehension. *Science*, *304*, 438–441.
- HALGREN, E., BAUDENA, P., HEIT, G., CLARKE, J. M., MARINKOVIC, K., & CHAUVEL, P. (1994). Spatio-temporal stages in face and word processing. 2. Depthrecorded potentials in the

- human frontal and Rolandic cortices. *J. Physiol. Paris*, *88*, 51–80.
- HALGREN, E., DHOND, R. P., CHRISTENSEN, N., PETTEN, C. V., MARINKOVIC, K., LEWINE, J. D., & DALE, A. M. (2002). N400-like magnetoencephalography responses modulated by semantic context, word frequency, and lexical class in sentences. *Neuroimage*, *17*, 1101–1116.
- HASSON, U., NUSBAUM, H. C., & SMALL, S. L. (2007). Brain networks subserving the extraction of sentence information and its encoding to memory. *Cereb. Cortex*, *17*, 2899–2913.
- HEIM, I., & KRATZER, A. (1998). *Semantics in generative grammar*. New York: Blackwell.
- HEIN, G., DOEHRMANN, O., MULLER, N. G., KAISER, J., MUCKLI, L., & NAUMER, M. J. (2007). Object familiarity and semantic congruency modulate responses in cortical audiovisual integration areas. *J. Neurosci.*, *27*, 7881–7887.
- HELENIUS, P., SALMELIN, R., SERVICE, E., & CONNOLLY, J. F. (1998). Distinct time courses of word and context comprehension in the left temporal cortex. *Brain*, *121*, 1133–1142.
- HOENIG, K., & SCHEEF, L. (2005). Mediotemporal contributions to semantic processing: fMRI evidence from ambiguity processing during semantic context verification. *Hippocampus*, *15*, 597–609.
- HOLCOMB, P. (1993). Semantic priming and stimulus degradation: Implications for the role of the N400 in language processing. *Psychophysiology*, *30*, 47–61.
- HUMPHRIES, C., BINDER, J. R., MEDLER, D. A., & LIEBENTHAL, E. (2007). Time course of semantic processes during sentence comprehension: An fMRI study. *Neuroimage*, *36*, 924–932.
- JACKENDOFF, R. (1997). *The architecture of the language faculty*. Cambridge, MA: MIT Press.
- JACKENDOFF, R. (1999). The representational structures of the language faculty and their interactions. In C. M. Brown and P. Hagoort (Eds.), *The neurocognition of language* (pp. 37–79). Oxford, UK: Oxford University Press.
- JACKENDOFF, R. (2002). *Foundations of language: Brain, meaning, grammar, evolution*. Oxford, UK: Oxford University Press.
- KEENAN, E. L. (1979). On surface form and logical form. *Stud. Linguist. Sci.*, *8*, 163–203.
- KIEHL, K. A., LAURENS, K. R., & LIDDLE, P. F. (2002). Reading anomalous sentences: An event-related fMRI study of semantic processing. *Neuroimage*, *17*, 842–850.
- KIM, A., & OSTERHOUT, L. (2005). The independence of combinatory semantic processing: Evidence from event-related potentials. *J. Mem. Lang.*, *52*, 205–225.
- KUPERBERG, G. R. (2007). Neural mechanisms of language comprehension: Challenges to syntax. *Brain Res.*, *1146*, 23–49.
- KUPERBERG, G. R., HOLCOMB, P. J., SITNIKOVA, T., GREVE, D., DALE, A. M., & CAPLAN, D. (2003). Distinct patterns of neural modulation during the processing of conceptual and syntactic anomalies. *J. Cogn. Neurosci.*, *15*, 272–293.
- [14] KUPERBERG, G. R., LAKSHMANAN, B. M., CAPLAN, D. N., & HOLCOMB, P. J. (2006). Making sense of discourse: An fMRI study of causal inferencing across sentences. *Neuroimage*, *33*, 343–361.
- KUPERBERG, G. R., MCGUIRE, P. K., BULLMORE, E. T., BRAMMER, M. J., RABE-HESKETH, S., WRIGHT, I. C., LYTHGOE, D. J., WILLIAMS, S. C., & DAVID, A. S. (2000). Common and distinct neural substrates for pragmatic, semantic, and syntactic processing of spoken sentences: an fMRI study. *J. Cogn. Neurosci.*, *12*, 321–341.
- [15] KUPERBERG, G. R., SITNIKOVA, T., & LAKSHMANAN, B. M. (2008). Neuroanatomical distinctions within the semantic system during sentence comprehension: Evidence from functional magnetic resonance imaging. *Neuroimage*, *40*, 367–388.
- KUTAS, M., & FEDERMEIER, K. D. (2000). Electrophysiology reveals semantic memory use in language comprehension. *Trends Cogn. Sci.*, *4*, 463–470.
- KUTAS, M., & HILLYARD, S. A. (1980). Reading senseless sentences: Brain potentials reflect semantic anomaly. *Science*, *207*, 203–205.
- KUTAS, M., & HILLYARD, S. A. (1984). Brain potentials during reading reflect word expectancy and semantic association. *Nature*, *307*, 161–163.
- KUTAS, M., VAN PETTEN, C., & KLUENDER, K. R. (2006). Psycholinguistics electrified. II. 1994–2005. In M. Traxler & M. A. Gernsbacher (Eds.), *Handbook of psycholinguistics* (2nd ed., pp. 659–724). Elsevier.
- LEVELT, W. J. M. (1999). Producing spoken language: A blueprint of the speaker. In C. M. Brown & P. Hagoort (Eds.), *The neurocognition of language* (pp. 83–122). Oxford, UK: Oxford University Press.
- LI, X., HAGOORT, P., & YANG, Y. (2008). Event related potential evidence on the influence of accentuation in spoken discourse comprehension in Chinese. *J. Cogn. Neurosci.*, *20*, 906–915.
- MAGUIRE, E. A., FRITH, C. D., & MORRIS, R. G. (1999). The functional neuroanatomy of comprehension and memory: The importance of prior knowledge. *Brain*, *122*, 1839–1850.
- MASON, R. A., & JUST, M. A. (2006). Neuroimaging contributions to the understanding of discourse processes. In M. Traxler & M. A. Gernsbacher (Eds.), *Handbook of Psycholinguistics* (pp. 765–799). Amsterdam: Elsevier.
- MCCARTHY, G., NOBRE, A. C., BENTIN, S., & SPENCER, D. D. (1995). Language-related field potentials in the anterior-medial temporal lobe. I. Intracranial distribution and neural generators. *J. Neurosci.*, *15*, 1080–1089.
- MCELREE, B., TRAXLER, M. J., PICKERING, M. J., SEELY, R. E., & JACKENDOFF, R. (2001). Reading time evidence for enriched composition. *Cognition*, *78*, B17–25.
- MONTAGUE, R. (1970). Universal grammar. *Theoria*, *36*, 373–398.
- MOSS, H. E., ABDALLAH, S., FLETCHER, P., BRIGHT, P., PILGRIM, L., ACRES, K., & TYLER, L. K. (2005). Selecting among competing alternatives: Selection and retrieval in the left inferior frontal gyrus. *Cereb. Cortex*, *15*, 1723–1735.
- NEWMAN, A. J., PANCHEVA, R., OZAWA, K., NEVILLE, H. J., & ULLMAN, M. T. (2001). An event-related fMRI study of syntactic and semantic violations. *J. Psycholinguist. Res.*, *30*, 339–364.
- NI, W., CONSTABLE, R. T., MENCL, W. E., PUGH, K. R., FULBRIGHT, R. K., SHAYWITZ, S. E., SHAYWITZ, B. A., & GORE, J. (2000). An event-related neuroimaging study distinguishing form and content in sentence processing. *J. Cogn. Neurosci.*, *12*, 120–133.
- NIEUWLAND, M. S., & VAN BERKUM, J. J. A. (2006). When peanuts fall in love: N400 evidence for the power of discourse. *J. Cogn. Neurosci.*, *18*, 1098–1111.
- OSTERHOUT, L., & HOLCOMB, P. J. (1992). Event-related brain potentials elicited by syntactic anomaly. *J. Mem. Lang.*, *31*, 785–806.
- OSTERHOUT, L., KIM, A., & KUPERBERG, G. R. (2007). The neurobiology of sentence comprehension. In M. Spivey, M. Joannisse, & K. McRae (Eds.), *The Cambridge handbook of psycholinguistics*. Cambridge, UK: Cambridge University Press.
- OSTERHOUT, L., McLAUGHLIN, J., & BERSICK, M. (1997). Event-related brain potentials and human language. *Trends Cogn. Sci.*, *1*, 203–209.

- PARTEE, B. H. (1984). Compositionality. In F. Veltman, & F. Landman (Eds.), *Varieties of formal semantics*. Dordrecht: Foris.
- 17 PARTEE, B. H., TER MEULEN, A., & WALL, R. E. (1990). *Mathematical methods in linguistics*. Kluwer.
- PYLKKÄNEN, L., & McELREE, B. (2007). An MEG study of silent meaning. *J. Cogn. Neurosci.*, *19*, 1905–1921.
- RODD, J. M., DAVIS, M. H., & JOHNSRUDE, I. S. (2005). The neural mechanism of speech comprehension: fMRI studies of semantic ambiguity. *Cereb. Cortex*, *15*, 1261–1269.
- RUSCHEMEYER, S. A., FIEBACH, C. J., KEMPE, V., & FRIEDERICI, A. D. (2005). Processing lexical semantic and syntactic information in first and second language: fMRI evidence from German and Russian. *Hum. Brain Mapp.*, *25*, 266–286.
- RUSCHEMEYER, S. A., ZYSSET, S., & FRIEDERICI, A. D. (2006). Native and non-native reading of sentences: An fMRI experiment. *Neuroimage*, *31*, 354–365.
- SEUREN, P. A. M. (1998). *Western linguistics: An historical introduction*. Oxford, UK: Blackwell.
- SIEBORGER, F. T., FERSTL, E. C., & VON CRAMON, D. Y. (2007). Making sense of nonsense: An fMRI study of task induced inference processes during discourse comprehension. *Brain Res.*, *1166*, 77–91.
- ST GEORGE, M., KUTAS, M., MARTINEZ, A., & SERENO, M. I. (1999). Semantic integration in reading: Engagement of the right hemisphere during discourse processing. *Brain*, *122*, 1317–1325.
- STURT, P. (2007). Semantic re-interpretation and garden path recovery. *Cognition*, *105*, 477–488.
- THOMPSON-SCHILL, S. L., BEDNY, M., & GOLDBERG, R. F. (2005). The frontal lobes and the regulation of mental activity. *Curr. Opin. Neurobiol.*, *15*, 219–224.
- THOMPSON-SCHILL, S. L., D'ESPOSITO, M., AGUIRRE, G. K., & FARAH, M. J. (1997). Role of left inferior prefrontal cortex in retrieval of semantic knowledge: a reevaluation. *Proc. Natl. Acad. Sci. USA*, *94*, 14792–14797.
- TRAXLER, M., McELREE, B., WILLIAMS, R., & PICKERING, M. (2005). Context effects in coercion: Evidence from eye movements. *J. Mem. Lang.*, *53*, 1–25.
- TRAXLER, M., PICKERING, M., & McELREE, B. (2002). Coercion in sentence processing: Evidence from eye movements and self-paced reading. *J. Mem. Lang.*, *47*, 530–547.
- VAN ATTEVELDT, N. M., FORMISANO, E., BLOMERT, L., & GOEBEL, R. (2007). The effect of temporal asynchrony on the multisensory integration of letters and speech sounds. *Cereb. Cortex*, *17*, 962–974.
- VAN ATTEVELDT, N., FORMISANO, E., GOEBEL, R., & BLOMERT, L. (2004). Integration of letters and speech sounds in the human brain. *Neuron*, *43*, 271–282.
- VAN BERKUM, J. J. A., VAN DEN BRINK, D., TESINK, C., KOS, M., & HAGOORT, P. (2008). The neural integration of speaker and message. *J. Cogn. Neurosci.*, *20*, 580–591.
- VIGNEAU, M., BEAUCOUSIN, V., HERVE, P. Y., DUFFAU, H., CRIVELLO, F., HOUDE, O., MAZOYER, B., & TZOURIO-MAZOYER, N. (2006). Meta-analyzing left hemisphere language areas: Phonology, semantics, and sentence processing. *Neuroimage*, *30*, 1414–1432.
- WAGNER, A. D., PARE-BLAGOEV, E. J., CLARK, J., & POLDRACK, R. A. (2001). Recovering meaning: Left prefrontal cortex guides controlled semantic retrieval. *Neuron*, *31*, 329–338.
- WILLEMS, R. M., ÖZYÜREK, A., & HAGOORT, P. (2007). When language meets action: The neural integration of gesture and speech. *Cereb. Cortex*, *17*, 2322–2333.
- WILLEMS, R. M., ÖZYÜREK, A., & HAGOORT, P. (2008). Seeing and hearing meaning: Event-related potential and functional magnetic resonance Imaging evidence of word versus picture integration into a sentence context. *J. Cogn. Neurosci.*, *20*, 1235–1249.
- XU, J., KEMENY, S., PARK, G., FRATTALI, C., & BRAUN, A. (2005). Language in context: Emergent features of word, sentence, and narrative comprehension. *Neuroimage*, *25*, 1002–1015.
- ZEMPLENI, M. Z., RENKEN, R., HOEKS, J. C., HOOGDUIN, J. M., & STOWE, L. A. (2007). Semantic ambiguity processing in sentence context: Evidence from event-related fMRI. *Neuroimage*, *34*, 1270–1279.



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