[REVIEW ARTICLE]

MODELLING NEURONAL GRAMMAR CIRCUITS

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The Neuroscience of Language: On Brain Circuits of Words and Serial Order, by Friedmann Pulvermüller, Cambridge University Press, New York, 2002, xiv+275pp.

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1. Introduction

Elucidating the underlying mechanisms within the brain for realising the human-language faculty remains one of the biggest issues in today's science. In modern theoretical linguistics, much effort has been devoted to the development of grammar/syntactic theories on the basis of stringent combinatorial rules as represented by the so-called PSGs (Phrase Structure Grammars), rooted in the pioneering works of Harris (1951, 1952) and Chomsky (1957), or Dependency Grammar due to Tesnière (1953, 1959). The appearance of such linguistic theories was sensational, and since then, theoretical linguists have seriously investigated these radical approaches and, where necessary, adjusted them to give (moderately successful) accounts for the exceptions encountered during application to real data/examples. However, the multiple revisions of the approaches have unavoidably yielded more complex rules, which quite often hinders us from straightforward application of the revised approaches and investigation of the results so obtained.

In the book under review, the motivation of Pulvermüller is to propose a multi-disciplinary and integrated approach towards building up a neuro-

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science basis of syntactic structures. In support of his attempt, recent advances in the theory of general cognitive neuroscience accompanied by the improvement in the measurement devices for brain dynamics have begun to shed additional light on the study of language. In my view, the theory of neuronal grammar/syntax developed in the latter part of the book is the outcome of his broad perspective from neurophysiology to neuronal modelling to linguistics and is firmly grounded in the multitude of new findings obtained within the modern neurophysiological/neurobiological context. As he admits at the very beginning of the book (p. 1), describing language in terms of neurons is not new and a number of such approaches have been proposed so far since the age of Freud (Freud (1891), Braitenberg (1980), Mesulam (1990), Schnelle (1996), amongst others). However, I still can see the uniqueness of this monograph amongst others in the manner of integration of different language-oriented studies into one unifying theory: the proposal of a neuronal grammar circuit supported by ample amounts of psycholinguistic and neuroscientific data collected using various modern instrumental measurement technologies. In this regard, Pulvermüller's approach does not end up with a mere connectionist modelling but is quite challenging in both cognitive/theoretical linguistics and general brain scientific research domains.

The book then emphasises the importance of conducting multi-disciplinary research in theoretical linguistics which can thereby give more unified and innovative accounts for various language phenomena observed for example in terms of relatively simple neuronal circuits.

1.1. Overview of the Book

The book consists of fourteen chapters and five "excursuses," the latter of which discuss some of the selected topics in more depth or polish the concepts developed in the earlier chapters but may be slightly away from the main topics of interest in the sequel of the chapters. Overall, the monograph can be divided into three parts: first, Chapters 2–7 give the motivation from various areas of neuroscientific/psycholinguistic research and thereby provide the foundation of the theory of neuronal grammar developed in the second part of the book in Chapters 8–12. Third, in Chapters 13 & 14, Pulvermüller makes some general remarks on the current trends in cognitive linguistics and suggest a few directions in the study.

In Chapter 1, the author begins with a concise summary of each chapter, and suggests three recommended "tours" through the book which partially cover the book chapters, depending upon the interest of the readers: i) "Neu-

roscience" for Chapters 2–5, 8–9, 13, and E1 (Excursus 1), ii) "Linguistics" for Chapters 4, 7–12, and 14, and iii) "Modelling" for Chapters 4–6 and E1–E5.

In the earlier part of Chapter 2, an introductory description of how the brain is organised is given from the bottom level of a single nerve cell (or neuron) to a macroscopic level of cortical areas. Later in the chapter, Pulvermüller introduces a new term "functional-web" (or, interchangeably, "cell assembly") to denote a large set of neurons distributed over a small set of cortical areas (p. 24).[1] The term "functional-web" then represents a particular concept related to the activity dynamics of the neurons within the actual brain, e.g. the neural activity when perceiving the word "cat." The notion of a functional-web is further exploited in both developing the theory of the neuronal circuits and describing their dynamics later in the book.

Chapter 3 introduces some neurological evidence on the laterality of language and traditional models of language faculty within the brain, both of which are firmly bound to neurological findings of aphasic patients. The latter part of the chapter focuses upon some of the recent advances in identifying the faculty of language within the brain by means of modern neuroimaging technology. In the succeeding chapter 4, the focus is then moved on to the neuroimaging studies of words in detail, and a version of the functional-web specific to word processing, "word-web," is newly introduced. Excursus 1 discusses how the clinical observation of double dissociations—for instance, an aphasic patient with severe deficits in producing oral language but less difficulty in its understanding—can be modelled by exploiting the concept of functional-webs. A simulation example using the model is also given. Chapter 5 refines the concept of word-webs mainly from a modelling scope. In the chapter, Pulvermüller also suggests that the idea of functional-webs gives general accounts for more interesting issues of homophones (Section 5.2.1), synonyms (Section 5.2.2), and emotional/affective meaning (Section 5.3.1).

In Chapters 6 & 7, the main focus is more shifted to the modelling side of the issues in language processing; some well-known models developed within

[1] Pulvermüller claims that the ''fuzziness'' residing in the definition of cell assemblies and functional-webs does not constitute a fundamental problem (p. 25). In my view, however, the meaning of this argument should be restricted to the following: there certainly exists a population of cells/neurons that co-activate together during a certain period of time for a particular purpose. However, due to the limit of currently available measurement technology, the accurate location of each such cell/neuron cannot be specified but only statistically measurable.

connectionism (in Chapter 6) and approaches proposed in the theoretical linguistics domain (in Chapter 7). Chapter 6 also gives a concise summary of the studies in ANNs (Artificial Neural Networks). Amongst which are the traditional model of McCulloch & Pitts' logical calculus circuits (McCulloch and Pitts (1943), Kleene (1956)) and MLP-NN (Multi-Layered Perceptron Neural Network) (Rumelhart et al. (1986), amongst others) with some applications to language-oriented problems of word category deficits and word inflections. In the chapter, Pulvermüller compares some well-known connectionist approaches and the McCulloch & Pitts' logical calculus model, the latter of which gave him a motivation for developing the neural grammar circuits in the latter part of the book. In contrast, Chapter 7 highlights two well-established linguistic approaches to syntax, i.e. PSG and dependency grammar, and gives a counter-argument against the traditional theoretical linguists' view about the inferiority of the McCulloch & Pitts' model.

Chapters 8 & 9 review some well-known neurocomputational models of serial order. Amongst many, the review (in Chapter 8) is focused upon the "synfire chain" model (Abeles (1991)), which can be thought of as a fundamental tenet for syntax representation within the brain. Pulvermüller also argues its fundamental weakness when it is extended to describe word sequences.

Chapters 10 & 11 provide the proposal of the neural grammar circuits. In Chapter 10, the concept of neural grammar circuits is firstly proposed by reflecting on various neuroscientific notions described in the earlier chapters. Chapter 11 shows how the neural grammar circuits developed in the previous chapter can be translated into a notion more familiar to linguists of assignment rules. Excursuses 2 & 3 are devoted to the description of how neuronal grammar circuits operate at a neuronal level is given, via the simulation examples of some simple sentences, as well as alternative representations using a set of assignment formulas (Excursus 2). In contrast, the simulation examples given in Excursus 3 are for the case where a more complex sentence is processed. The design of neuronal grammar circuits is slightly modified in Chapter 12, with the introduction of multiple activity states of a neuronal set, and then the modified model is shown to be extensible to give convincing accounts for the three cases:

i) the distinction between constituent's obligatory complements and its optional adjuncts,
ii) the multiple occurrence of the same word form in a string,
iii) multiple centre embedding.

Excursus 4 describes how case ii) in the above (i.e. the case where lexical

ambiguity resides) can be resolved in terms of the activity dynamics of the neuronal circuit in detail, whilst the sentences with multiple centre embedding (case iii)) are shown to be processed with no failure by the neuronal grammar circuits given in Excursus 5.

In Chapter 13, an overview of some previous neurophysiological works related to syntax, as well as the author's perspective for future study, are given, the former of which can somewhat be seen as a reminiscence from the earlier part of the book. In addition, the author suggests a general framework for the empirical justification of the neuronal grammar theory by means of modern neuroimaging technology, which is however left for the future studies. Finally, in Chapter 14, Pulvermüller's current view of the relation between theoretical linguistics and neuroscience studies is described.

As seen in the overview above, Pulvermüller's study integrates various disciplines relevant to theoretical linguistics, with the use of currently available instrumental measurement technologies as much as possible, into a unique and consistent research framework and eventually derives the theory of the brain circuits that represent the processing relevant to the language faculty. The purpose of this review article is therefore to examine carefully the main thrusts of the present book, namely the two proposals of functional-/word-webs and neuronal grammar circuits, mainly from a modeller's point of view, whilst reviewing some of the key neuroscientific evidence relevant to language processing which appeared mostly in the earlier part of the book (Chapters 2–5).

In the following section 2, a quick review of some key facts known so far about language processing within the brain is given. In Section 3, I will move on to a careful examination of the neural grammar circuit which was proposed with the support of the neuroscientific findings described in Chapters 2–5. In Section 4, I will first begin with a rather critical review of one of the well-known artificial neural network models, i.e. MLP-NN which has been widely applied in various theoretical linguistic problems, rather from the engineering view point. This may hopefully supplement Pulvermüller's original arguments given in Chapter 6. In the second half of Section 4, another approach of RBF (Radial Basis Function) based connectionist models is introduced. As will be described, such an approach can give solutions to various problems inherent to MLP-NN. I will then argue why RBF based models may provide a better alternative for neural modelling of language in terms of neural plausibility and modelling both the perceptual and post-perceptual activities.

2. What Is Known so far About Language Processing Within the Brain? —Some Evidence from Neuroscientific Studies

As supported by a number of neurological and neuroimaging studies (p. 13), it is generally known that the part of the brain most relevant for language is the cerebral cortex. Neuroanatomically, the human cortex can be roughly divided into two hemispheric parts: left and right cortical hemispheres. For language processing, the left hemisphere is said to be dominant in the large majority of individuals, as justified by means of modern neuroimaging technologies (Zatorre et al. (1992), Petersen and Fiez (1993), Näätänen et al. (1997), Shtyrov et al. (2000)). However, it is also said that such language laterality is rather gradual, according to the studies using MEG (MagnetoEncephaloGraphy), multichannel EEG (ElectroEncephaloGraphy), and fMRI (functional Magnetic Resonance Imaging) (p. 40, Pulvermüller (1999)). Moreover, some neuropsycological studies imply that the right hemisphere even contributes to the fundamentals of language processing. For instance, distinction of words from meaningless material can be reliably performed by the right hemisphere (p. 42, Zaidel (1976, 1985)). In relation to this, it is considered that additional information processing occurs within the nondominant hemisphere (right) in order to help optimising the word processing within the dominant (left) hemisphere (Pulvermüller and Mohr (1996), Hasbrooke and Chiarello (1998)).

Apart from the aforementioned studies based upon the left and right hemispheric partitions, each hemisphere can be subdivided into approximately 50 to 100 areas (p. 14 Figure 2.3, Brodmann (1909)), or, from another view, the human cortex is partitioned into four lobes: i) the frontal lobe: upper left, ii) parietal lobe: top, iii) occipital lobe: back, and iv) temporal lobe: bottom (see also Gazzaniga et al. (2002: 72 Figure 3.9)). In general, such subdivisions are made dependent upon the study of interest. Amongst the aforementioned four lobes, both the frontal and temporal lobes are considered to be most crucial for language, the areas of which exhibit a smaller volume of white matter (that is made up primarily of axons and their glia sheaths) in the left hemisphere (p. 41). In contrast, as many clinical observations have indicated, the so-called areas of i) Broca (Brodmann's 44 and 45 areas, in the inferior frontal lobe: Broca (1861)), ii) Sylvian fissure (the boundary running horizontally below the Broca's area), and iii) Wernicke (Brodmann's 22, 39, and 40 areas, spread to both the temporal and parietal lobes; Wernicke (1874)) areas are anatomically considered as the central areas for language processing (p. 35).

In general, these aforementioned studies are fundamental for analysing the brain activities relevant to language processing.

2.1. Neuron: as the Functional Element of the Brain

In general cognitive neuroscience, the most fundamental element within the brain is conceived as a "neuron" that consists of dendrites, a cell body, and axon. A neuron then receives signals from others through the dendrites and eventually transmits its own signals to other neurons via the axon and its branches (p. 10). The human cortex is said to contain more than 10 billion neurons (p. 13, p. 23, Braitenberg and Schüz (1998)). Thus, the human cortex is topologically considered as a fairly large-scale complex system that consists of numerous numbers of nodes (i.e. represented by neurons) and their mutual interconnections (i.e. the synaptic connections).

2.2. The Notion of Functional-Web

With the aforementioned neuroscientific findings behind, Pulvermüller (p. 24) then introduces the concept of functional-web in modelling higher brain processes, as a set of cortical neurons

i) that are strongly connected to each other
ii) that are distributed over a specific set of cortical areas
iii) that work together as a functional unit
iv) whose major parts are functionally dependent on each other so that each of them is necessary for the optimal functioning of the web.

Throughout the book, the term "functional-web" is used to specify a particular large set of neurons distributed over a small set of different cortical areas (p. 24), which eventually constitutes a neuronal network within the brain exhibiting a particular functionality, e.g. the functional-web representing the concept of the word "cat" (hence, the "word-web" of "cat" concept). Pulvermüller further postulates that such a functional-web may also establish the connections with neurons within the amygdala and midbrain, both areas of which are considered to play a significant role in representing the emotional/affective properties of words (Section 5.3).

In the above, the first claim i) reflects the neurophysiological evidence that the adjacent neurons are heavily connected and thereby form local clusters (p. 21). According to the neurophysiological findings by Hubel (1995), for instance, a group of neurons within a column of visual cortex respond to similar visual stimulus features. Then, the work due to Hubel can give empirical evidence for both claims iii) and (partially) iv) in that neurons in

a local cluster (called a "column") exhibit similar functional characteristics and must therefore be functionally dependent upon each other. In respect of the functional dependence, Pulvermüller also gives a postulate that, as individual neurons are too noisy and unreliable computational devices, large neuron ensembles should cooperate together for achieving reliable information processing (p. 23).

Now, let us turn to some of the studies on a more macroscopic level of connections for claim ii), i.e. the cortical-level connections. In the animal study of macaque monkeys, it was found that the adjacent areas of primary motor and somatosensory cortices have direct synaptic connections with a high probability (Young et al. (1995)), whilst most of the other primary cortical areas are not directly connected to each other (Pandya and Yeterian (1985)). By taking these empirical facts into account, it is possible to conjecture (in the phylogenetic sense) that the neurons within the primary auditory cortex and primary motor cortex in human brains are connected to each other via the "relay neurons" (p. 28) within the inferior frontal lobe (Brodmann's areas 44 and 45) and those within the superior temporal lobe (Brodmann's areas 22 and 42) (Pandya and Yeterian (1985), Deacon (1992)). By generalising this notion, it is then considered that such relay neurons are crucial for not only establishing (unidirectional) connections between actions and auditory input but also mutual associations amongst other modalities, such as auditory-visual, somatosensory-visual, and visual-action (p. 18). Since the mapping between primary areas is indirect, the relay neurons may greatly contribute to storing complex relationships between input and output patterns (p. 21). In support of this view, according to the neurophysiological studies (Fuster and Alexander (1971), Fuster and Jervey (1982)), a group of neurons that respond to a particular stimulus input and then show similar dynamics were found in the prefrontal cortex (i.e. the area responsible for action control), as well as in the inferior temporal lobe (i.e. the area responsible for perception) of macaque monkeys; a near-exponential decrease of neuronal activity was observed after their stimulus-driven activation. On the other hand, the rich history of neurological investigation into language disorders, i.e. aphasias, the symptoms of which mostly appear to be multimodal, including deficits in producing and comprehending spoken language and those in both reading and writing (p. 34), (Broca (1861), Lichtheim (1885), Wernicke (1874)), can provide another strong evidence for the concept of word-webs, in that the areas in both the prefrontal and temporal lobes are jointly most crucial for the language processing (p. 28). In summary, these investigations generally support the remaining claim ii) above

in the sense that there are neurons with cross-cortical connections which thereby cooperate together for a particular information processing.

On the basis of these neuroscientific findings/investigations, it is not implausible that higher brain processes are realised by functional units above the level of a single neuron (p. 22, Hebb (1949)), i.e. a certain large set of neurons, which then led Pulvermüller to define the concept of a functional-web. Moreover, such a view may be extended to provide an eloquent account for the controversial issue of perception: the reason why the cognitive postulate of single mother's cell is not feasible (i.e. the concept of "mother", for instance, is represented by a single cell; e.g. see Gazzaniga et al. (2002: 211)).

2.3. Temporal Dynamics in a Functional-Web

Pulvermüller then moves on to a discussion of temporal dynamics in a functional-web, based upon some theoretical investigations into the models of associative memory (p. 29). Since the cortex is considered to be an associative memory allowing for merging information from different modalities (which is driven by the correlation of spatiotemporal patterns of neuronal activity) (p. 28), defining the temporal dynamics in a functional-web can naturally follow. Moreover, for a particular perceptual processing, for instance, Pulvermüller's concept of an associative memory could even be exploited to model the psychological sense of "Gestalt completion" phenomena (p. 29, Willshaw et al. (1969)).

In summary, the following four states characterise the temporal activity dynamics of a functional-web:

i) *ignition*: the state of activity in which stimulation of a fraction of neurons leads to a full activation of the entire population of neurons (p. 29, p. 170, Braitenberg (1978), Palm (1981, 1982)),

ii) *reverberation*: the state in which the neuronal assembly retains its activity with the level of activity falling off exponentially with time, after an initial brief ignition (p. 32),

iii) *priming*: the state representing the subthreshold activation of a functional-web as a result of the input from one or more other neuronal sets (p. 170),

iv) *inactivity*: the resting state of a functional-web

Related to state ii) above, the empirical fact obtained from the memory task experiment using a monkey (Fuster (1995)) provides the evidence that the memory interval of reverberatory activity can last for tens of seconds (p. 32). In addition to this, it is postulated that massively reverberatory circuits

produce precisely and timed high-frequency rhythms when they are active (p. 53, Milner (1974), von der Malsburg (1995), Pulvermüller et al. (1997), Tallon-Baudry and Bertrand (1999)), as justified by the neuroimaging studies using EEG/MEG (Krause et al. (1998), Eulitz et al. (2000), Pulvermüller (2001), amongst others) within the context of word/pseudo-word discrimination tasks. These studies can then provide strong support for the existence of word-specific functional-webs (or "word-webs") in the actual brain.

In conclusion, taking the line of the supportive neurophysiological studies as reviewed in this section, the notion of a functional-/word-web and the aforementioned four states i)–iv), describing the temporal activity dynamics in functional-webs, sufficiently reflects the current neuroscientific view of language and thus can give a reasonable basis for modelling the information processing relevant to language occurring within the brain. The notion of functional-/word-web is extensively exploited in modelling neuronal grammar circuits appeared in the later part of the book.

In the following section, I then move on to examine the core proposal of neuronal grammar circuits.

3. Neuronal Circuits Representing Grammar

As Kinoshita (1996: Chapter 6) pointed out, to represent syntactic structures in terms of neurons, it is first of all deemed to be crucial for considering how such a sequence detection mechanism is represented in the neural modelling of grammar (cf. the argument in the beginning of Section 9.3 in p. 163). In the actual brain, however, the smallest unit for the perception of language sounds still is not known (and therefore remains a matter of debate) (Ōtake (1995: 134))—it may be a phoneme, sub-word, or something else. At a glance, one may feel that here we are totally at a loss for finding an appropriate clue in modelling the sequence detection mechanisms for language processing. In my opinion, however, this is not the case, and it is in turn good for us to depart from the conjecture that the smallest unit *is* a phoneme (or sub-word). This will be worthwhile, if (as a general rule) the model(s) proposed based upon such a conjecture can give more eloquent accounts for various aspects of language processing than existing approaches. On this basis, one of the promising approaches is to imitate such a detection mechanism using an artificial neuronal network (or connectionist) model to be described next, perform the simulation study (as also given in the latter part of the present book), and discuss the results obtained in due course.

3.1. Detection of Serial Order for a Word Sequence

In Chapter 8, Purlvermüller begins with the so-called "synfire chain" model (Abeles (1991)), which was proposed as the putative mechanism within the brain for realising a serial order processing: e.g. event A first occurs and then B does. A synfire chain can be composed of a total of around 50–100 neurons (Diesmann et al. (1999), p. 149 Figure 8.1) and applied to detect a sequence of behaviours (Lashley (1951)) or the phonemes of a word (e.g. the word "cat"; the sequence of phonemes: [k], [æ], and followed by [t]; p. 152). Then, it is argued that such chains may be found in functional-/word-webs (p. 156). On the other hand, it is described how McCulloch & Pitts' logical circuit which appeared in Chapter 6 (p. 101 Figure 6.2) can also be regarded as a biologically plausible model of serial order, with the supportive neurophysiological findings of similar mechanisms in cerebellar Purkinje cells or the visual system of arthropods and vertebrates (Reichardt and Varju (1959), Barlow and Levick (1965), Hubel (1995), Braitenberg et al. (1997), amongst others). Pulvermüller claims that, unlike synfire chains, the sequence detector modelled by McCulloch & Pitts' circuit requires only a few neurons (p. 101 Figure 6.2).

However, as he argued in Section 9.2, at the moment, it seems to be compelling that neither of the two can fully explain a sequence detection mechanism for a larger time scale (e.g. a scale spanning tens of seconds) such as the detection of word strings (Section 9.2). Then, he instead proposes a sort of trade-off on the basis of the neurophysiological findings obtained so far—detection mechanisms of a word sequence can be found at the level not of individual neurons but of a population of them; in his term, the corresponding functional-web, the functionality of which may be common in the perisylvian cortex (p. 167). Nevertheless, it is not denied that both the synfire chains and networks similar to the McCulloch & Pitts' circuits still hold some strong neurophysiological evidence for the sequence detection.

In Section 9.3, Pulvermüller moves on to a comparison of the neural sequence detection mechanism with a traditional phrase (or tree) structure representation. He then claims that the tree representation is not economical in the sense that it requires both the tree construction and within-tree transport of features, whereas syntactic structures can be represented by a unified mechanism of neuronal wiring within functional-webs (p. 164). In this limited sense, this is considered to be a generally acceptable notion. Then, he continues that difficulties arise in explaining certain aspects of syntactic priming effects by existing syntactic theories (p. 165, Pickering and Branigan (1999)), though to confirm this seems to require a more thorough justi-

fication.

3.2. Neuronal Grammar Circuits Based Upon the Sequence Detection of Lexical Categories

In Section 10.6, Pulvermüller introduces the concept of mediated sequence detection mechanism to the representation of serial order for lexical categories[2] by applying the notion of temporal dynamics in functional-webs. Then, this yields the fundamental idea in developing his neuronal grammar circuits.

It should be noted that the notion of introducing serial order by means of avoiding individual lexical items but exploiting categories is quite useful, (at least) from a modelling perspective (cf. Hoya (2005: Section 9.2.3)). In other words, this conjecture can be intuitively drawn (albeit putting aside its biological/neurophysiological justifiability) by considering a dramatic decrease in the number of entities required for constituting the sequence mechanisms in a grammar of language (e.g. for a single language including 100,000 word forms/morphemes, say, the number of lexical categories can be estimated to be around 100; for the approximation in detail, see p. 192 Table 10.2).

Next, to be more concrete, let us examine the following simple sentence in terms of Pulvermüller's neuronal grammar circuit:

(1) Alexandra wakes up.

The fragment of the neuronal circuit accepting this simple sentence can be illustrated as follows (cf. p. 217 Figure E2.1):

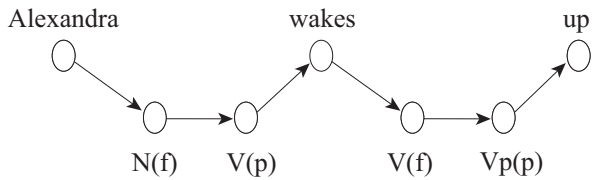

Figure 1. Fragment of the neuronal grammar circuit that accepts the sentence: "Alexandra wakes up." (cf. p. 217 Figure E2.1)

[2] In Pulvermuller's neuronal grammar circuit, it seems that there is no fundamental difference in implementing the serial orders for lexical and functional categories (nor in the translation into assignment rules as given in Chapter 11), which is however an important issue in theoretical linguistics domain. To justify this, a rigorous analysis and justification would be necessary, which is beyond the scope of the present review article.

In Figure 1, each circle is depicted as a population of neurons, rather than a single neuron, for representing the corresponding word, the arrows indicate the existence of (rather unidirectional) connections between the populations, and the symbols N(f), V(f), V(p), and Vp(p) denote the lexical categories of noun/verb with the expectation that a "forward sentence feature" follows (i.e. the former N(f) and V(f); p. 210), and the categories of verb/verb particle followed by a "backward sentence feature" (i.e. the latter V(p) and Vp(p)), respectively.

Alternatively, the neuronal grammar circuit as shown in Figure 1 can be translated into the following dependency grammar like set of the three formulas; assignment (2)–(4), valence (5)–(7), and sequence formula (8) and (9) (cf. (10)–(17) in pp. 216–217):

(2) Alexandra ⟷ N (noun)
(3) wake(s) ⟷ V (verb)
(4) up ⟷ Vp (verb particle)
(5) N (/*/ f)
(6) V (p /*/ f)
(7) Vp (p /*/)
(8) N(f) → V(p)
(9) V(f) → Vp(p)

In (5), the lexical category of noun is characterised by a lexical item followed by a single forward sentence feature (i.e. represented by the letter "f" within a pair of the parentheses), whereas that of verb as given in (6) has both the forward and backward (i.e. denoted by the letter "p") sentence features. Then, as in (8) and (9) above, a sequence formula has a single-sided arrow ("→") representing a specific serial order of the two lexical items; Formula (8) can be transcribed as "the population of neurons representing the lexical category of noun connected to that of the verb category."

In Excursuses 3–5, the original neuronal grammar circuits are refined, by allowing multiple levels in both the priming and reverberating states, and exploited further to give accounts for the case of lexical ambiguity, such as where i) discontinuous constituents/words (Section 7.3), ii) multiple occurrence of the same word but with different lexical categories, and iii) multiple centre embeddings (Section 7.2) appear in a processed sentence. The simulation studies at a more microscopic level of neuronal activity dynamics in the neuronal grammar circuits for these cases, as well as their dependency grammar transcriptions, are then presented within the respective excursuses. Figures 2 and 3 illustrate respectively the fragment of the neuronal circuit that accepts the sentence including discontinuous words (in the figures,

each number within each pair of curly braces representing the corresponding lexical category indicates the priming/reverberation level):

(10) Alexandra turns the switch off.

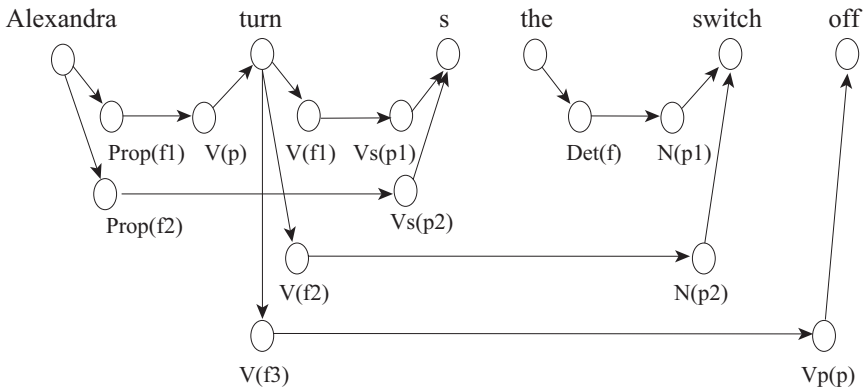

Figure 2. Fragment of the neuronal grammar circuit that accepts the sentence: "Alexandra turns the switch off." (cf. p. 228 Figure E3.1)

and the fragment of the circuit for the following sentence with multiple centre embeddings:

(11) Alexandra who Tomas who Lisa helps loves wakes up.

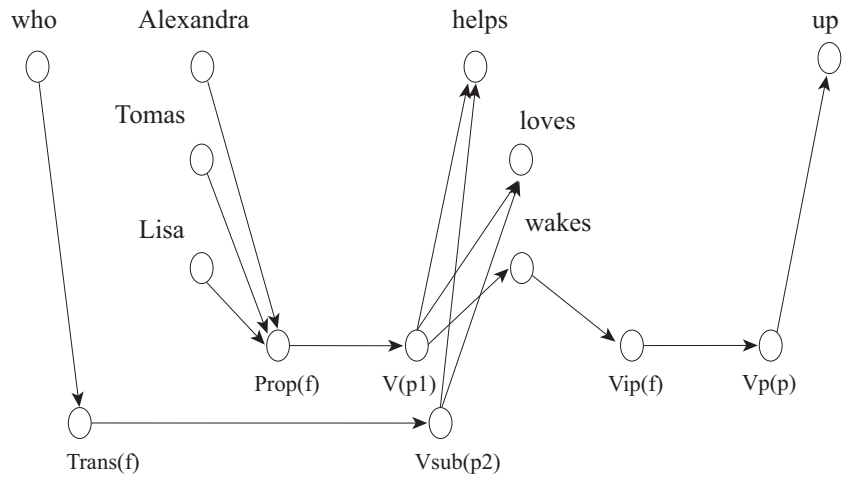

Figure 3. Fragment of the neuronal grammar circuit that accepts the sentence: "Alexandra who Tomas who Lisa helps loves wakes up." (cf. p. 256 Figure E5.1)

(For the network dynamics in detail and alternative representations of the neuronal circuits as shown in Figures 2 and 3 by the dependency grammar like rules, see Excursus 3 and 5.) Then, it is obviously seen that these neuronal circuit representations are not only conceptually intuitive but also applicable to visualise precisely how the processing of such intricate sentences can be explained by means of the activity dynamics of the nodes in neuronal networks.

As seen so far, it is said that Pulvermüller's concept of neuronal grammar circuits has been proposed with the support of a rich amount of various neuroscientific data obtained so far and with a line of simulation examples for the neuronal processing of some intricate sentences, the issues of which are also central to modern theoretical linguistic domains. The proposal is then accompanied by both the extensive simulation studies/further justifications made in Chapters 10–12 & Excursuses 2–5 and the comparison with the existing formalists' accounts such as PSGs and syntactic trees (as described in Chapter 7).

However, as he admits (pp. 263–264), there still remain some fundamental issues to be addressed in a further study: i) how the absence of overt translatives (p. 264) is processed and ii) whether the proposal of neuronal grammar circuits can be universally applicable to give accounts for other interactive cognitive modalities; semantic representations of words (p. 264) or perceptual processing of auditory/visual sensory data, the latter of which is also relevant to the issues of pattern recognition by ANNs described in the following section.

4. Artificial Neural Network Models for Language

As aforementioned, Pulvermüller's neuronal grammar circuit developed in Chapter 10 is based upon the traditional ANN model of McCulloch & Pitts' logical calculus. In Chapter 6, some other well-known ANN models for language problems are also described.

In this section, I firstly give a rather critical review of the most widely-known model amongst theoretical linguists, i.e. the MLP-NN, then compare with another approach of RBF (Radial Basis Function) based models, which are not discussed in the present monograph, and finally describe how RBF based models could benefit the further advances in modelling language phenomena.

4.1. MLP-NN

One of the well-acknowledged ANNs, or probably the most widely spread connectionist model amongst theoretical linguists, is MLP-NN, an extended version of the classical Rosenblatt two-layered perceptron network (Rosenblatt (1959)), and, as described in Sections 6.3 and 6.4, MLP-NNs have been applied to model various aspects of language processing. A typical MLP-NN model has a feed-forward structure consisting of three layers (i.e. input, hidden, and output layers, respectively) of multiple nodes (representing neurons), each of which outputs an analog value (i.e. approximated by an s-shaped or sigmoidal function), rather than binary. Then, the neurons in each layer are connected only to those in the subsequent layer, with weighted connections (or simply "weights") in between which are normally tuned by the so-called "backpropagation" algorithm so that the network yields the desired input-output mapping. Since the middle '80s, the MLP-NN has been a representative connectionist model in various disciplines, due to its simple architecture, and applied extensively to various problem domains.

However, within the engineering context, it is now well known that MLP-NNs are not always capable enough to handle the problems of interest (cf. Pinker (1999)), which is considered to be mostly ascribed to the numerical instability inherent to a gradient-descent iterative parameter tuning method, such as the backpropagation algorithm, during the network parameter tuning (cf. Marcus (2001: Chapter 2), Hoya (2005: Chapter 2)). On the other hand, recently it has also been a matter of debate from a cognitive neuroscientific view point, in that i) whether the implementation of backpropagation algorithm is biologically plausible is still not clear (cf. Stork (1989), Marcus (2001: Chapter 2)) and that ii) the strict-sense of modularity as in MLP-NNs is not that appealing (cf. Section 6.3, Pinker (1999)).

Moreover, in the neurophysiological study due to Hopfield (1995), it is suggested that to recognise an object the functional unit based upon an RBF, which can be composed by a population of spike neurons, yields a more powerful biological device, rather than a sigmoidal function as exploited in MLP-NNs. His view then appears very encouraging, as it can neurobiologically support the notion that the RBF based connectionist models, which will be discussed in the following subsection, could potentially be a fundamental basis for representing various cognitive functionalities and thus are considered to play a significant role for modelling various language-oriented processing occurring within the brain.

4.2. RBF Based Connectionist Models

In terms of design, an RBF is nothing more than a Gaussian distribution function in the probabilistic sense, which then acts as a similarity measurement between the input data given and the template data stored as the centroid vector, which has been widely exploited to form the so-called RBF-NNs (RBF Neural Networks) (Moody and Darken (1989), amongst others). Similar to an MLP-NN, a traditional model of RBF-NN is a three-layered feed-forward type network consisting of input, hidden, and output layers, whereas, unlike an MLP-NN, the hidden and output neurons are represented by the RBFs and linear sum operators, respectively, instead of all sigmoidal functions. In other words, the RBF-NN model is not completely a distributed connectionist model but rather can be seen as a hybrid of the distributed and localist connectionist model, in the sense that each hidden neuron (RBF) itself locally holds the template data. In contrast to the hidden neurons, the weight connections between the hidden and linear output neurons are somewhat distributed, each of which eventually represents the degree of certainty in the template data stored within the corresponding RBF and the class ID represented by the linear output neuron. Moreover, it can be seen that, since the hidden layer composed by "a population of" RBFs can have multiple representatives of the same class, the model is less likely to be of the form of a single-mother's cell but much closer to that of an ensemble coding scheme (cf. Gazzaniga et al. (2002)).

Taking these into consideration, the "kernel memory" model was proposed (Hoya (2004, 2005)), which can also be regarded as a variant of RBF networks. However, the kernel memory is fundamentally different from the conventional RBF based models in the following:

i) Lateral connections amongst RBFs are considered, unlike the family of RBF-NNs or MLP-NNs, and thereby in principle no topological constraint is present in the network structure, which could lead to a more life-like representation of neural network. Then, for instance, a kernel memory network can be self-structured by applying the Hebbian-motivated learning algorithm to be mentioned in iii) as in the below.

ii) Unlike traditional RBF-NN models, a simultaneous multiple domain data processing is possible within a single model of kernel memory, as each RBF can accept input data of different dimensionalities. (This extension can then remove the strict sense of modularity as well.) Moreover, the desirable features of incremental learning (cf. Macwhinney (2001: Section 3)) and

accommodation of new classes (categories) (cf. Hoya (2003)), especially in pattern recognition domain, are also straightforwardly possible within the context of kernel memory, which are generally hard to achieve by means of conventional learning algorithms for MLP-NNs or associative memory.

iii) The connections between RBFs can be trained by the non-iterative algorithm motivated from the traditional Hebbian learning principle (Hebb (1949), Hoya (2004, 2005)), and thereby no numerical instability is involved during the tuning of the network parameters; in the training phase, an input pattern will be automatically added to the system, where it is found to be appropriate, and immediately functions as a new constituent of the system. Moreover, the (biological affirmative sense of) reciprocal (or asymmetric) connections (cf. p. 110) between a pair of the nodes (here, the nodes not limited to ordinary RBFs but represented by any other linear/non-linear functions) can also be exploited within kernel memory.

iv) Within the artificial mind system (Hoya (2005)) context, the concept of kernel memory can be exploited further to model the (loosely distinct) modules of mind (cf. Fodor (1983), Hobson (1999)), with the aforementioned properties of kernel memory in i)–iii) above.

Related to the kernel memory, it has been shown in the recent article (Hoya and Washizawa (2007)) that an artificial neural network system which acts as a simultaneous multi-domain pattern associator and classifier constructed based upon kernel memory can achieve a superior performance, in comparison with one of the state-of-the-art machine learning methods of support vector machines (Vapnik (1996), amongst others).

Then, up to this point, we may envisage a model of perceptual processing: the simultaneous multi-domain pattern associator and classifier can be a functional element within a certain word-web(s) which, for example, plays the central role in establishing associative (or dual-domain) connections between auditory and visual sensory data acquired, as well as perceptual processing of the respective data domains (i.e. represented by the sub-networks within a particular word-web responsible for the pattern recognition tasks).

The discussion so far has been mainly concentrated around why RBF based models could be a better alternative in the view of neural plausibility and advantages mainly in modelling perceptual activities, both of which are essential to general language processing. Turning back to Pulvermüller's

original neuronal circuit concept, it is not clear if the concept can be also extensible to give concrete accounts for not only syntactic structures (or post-perceptual processing) but also the perceptual processing as discussed above. Moreover, note that the post-perceptual processing, sequence detection of the recognised linguistic elements, can also be carried out, by measuring the similarity between the spatio-temporal activation pattern input (i.e. obtained from a population of neurons responsible for the respective lower perceptual activities) to an RBF, which represents a particular serial-order of lexical/functional items recognised at the perceptual level, and the template data stored as a centroid vector of the RBF which generalises a particular category of serial-orders (cf. Hoya and Toyoda-Akiho (2006)). Such a framework could be consolidated further by introducing the concept of multiple activity states, similar to the one in the present monograph, within the activation output of each RBF, which is currently under investigation.

5. Conclusion

In this review article, I have firstly carefully examined the two main proposals of the book, namely both the concept of functional-/word-webs and the neuronal grammar circuits, mainly from a modeller's viewpoint, whilst reviewing some of the key neuroscientific findings/investigations obtained so far. Then, I have given a rather critical review of the well-known model of MLP-NN amongst psycho-/theoretical linguists and suggested that the models based upon RBFs could potentially take place/give further accounts for modelling various phenomena relevant to language, especially in terms of both the perceptual and post-perceptual (or syntactic processing) activities.

As Pulvermüller pointed out in the book, the studies based upon neural models have not been vigorously conducted so far in theoretical linguistics. This can perhaps be the combined result of, as the author also indicated in the concluding chapter of the book (p. 271), the following two reasons:

i) The models within the ANN context are still not powerful enough to explain various linguistic data obtained.
ii) Due to the current limited availability of measurement technology for brain analysis, we are still not at the stage of discussing language in terms of neurons.

Related to i) above, there may be another reason, since the MLP-NN model has been so pervasive that unfortunately the term connectionism has become almost a synonym of only a single kind of ANN model, i.e.

the MLP-NN (Marcus (2001: Preface)), amongst researchers. However, I would like to stress that we should not ignore the recent advances in connectionism; some models other than MLP-NN, such as the aforementioned RBF based models, have been found to be convincing, especially in the general pattern recognition domain, and have come to be acknowledged as promising connectionist models alternative to the conventional MLP-NN, within both the neurocomputational and neurophysiological contexts.

Besides, note that, in order to fully uncover up-to-the-minute details of the processing within the brain for various language-oriented phenomena, further technological advances are essential for achieving a leap forward, as well as more theoretical investigations via the modelling (cf. the argument in the middle of p. 178).

Although, as aforementioned, there is certainly a boundary between the approaches within theoretical linuguistic and those within neuroscientific research domains, a shared view is still held within both domains in the sense that there must be essentially a unique law or principle governing the language faculty of humans, which is eventually realised in terms of neuronal networks within the brain (cf. the argument in p. 9), regardless of any particularities of a single language.

REFERENCES

Abeles, Moshe (1991) *Corticonics—Neural Circuits of the Cerebral Cortex*, Cambridge University Press, Cambridge.

Barlow, Horace and William R. Levick (1965) "The Mechanism of Directionally Selective Units in Rabbit's Retina," *Journal of Physiology* 178, 477–504.

Braitenberg, Valentino (1978) "Cell Assemblies in the Cerebral Cortex," *Theoretical Approaches to Complex Systems*, ed. by Roland Heim and Günther Palm, 171–188, Springer, Berlin.

Braitenberg, Valentino (1980) "Alcune Considerazione Sui Meccanismi Cerebrali del Linguaggio (Some Consideration of the Mechanisms of Cerebral Cortex for Language)," *L'accostamento Interdisciplinare Allo Studio del Linguaggio*, ed. by Giorgio Braga, Valentino Braitenberg, Carlo Cipolli, Eugenio Coseriu, Stefano Crespi-Reghizzi, Jacques Mehler and Renzo Titone, 96–108, Franco Angeli Editore, Milano.

Braitenberg, Valentino, Detlef Heck and Fahad Sultan (1997) "The Detection and Generation of Sequences as a Key to Cerebellar Function: Experiments and Theory," *Behavioral and Brain Sciences* 20, 229–245.

Braitenberg, Valentino and Almut Schüz (1998) *Cortex: Statistics and Geometry of Neuronal Connectivity*, 2nd ed., Springer, Berlin.

Broca, Paul (1861) “Remarques sur la siege de la facultè de la parole articulèe, suivies d’une observation d’aphèmie (perte de parole) (Loss of Speech, Chronic Softening and Partial Destruction of the Anterior Left Lobe of the Brain),” *Bulletin de la Sociètè d’Anatomie* 36, 330–57.

Brodmann, Korbinian (1909) *Vergleichende Lokalisationslehre der Großhirnrinde* (Localisation in the Cerebral Hemispheres), J. A. Barth, Leipzig.

Chomsky, Noam (1957) *Syntactic Structures*, Mouton, The Hague.

Deacon, Terry W. (1992). “Cortical Connections of the Inferior Arcuate Sulcus Cortex in the Macaque Brain,” *Brain Research* 573(1), 8–26.

Diesmann, Markus, Marc O. Gewaltig and Ad Aertsen (1999) “Stable Propagation of Synchronous Spiking in Cortical Neural Networks,” *Nature* 402, 529–533.

Eulitz, Carsten, Hind Eulitz, Burkhard Maess, Rudolf Cohen, Christo Pantev and Thomas Elbert (2000) “Magnetic Brain Activity Evoked and Induced by Visually Presented Words and Nonverbal Stimuli,” *Psychophysiology* 37, 447–455.

Fodor, Jerry. A. (1983) *The Modularity of Mind: An Essay on Faculty Psychology*, MIT Press, Cambridge, MA.

Freud, Sigmund (1891) *Zur Auffassung der Aphasien* (On Aphaisa), Franz Deuticke, Leipzig.

Fuster, Joaquin M. and Garrett E. Alexander (1971) “Neuron Activity Related to Short-Term Memory,” *Science* 173, 652–654.

Fuster, Joaquin M. and John P. Jervey (1982) “Neuronal Firing in the Inferiotemporal Cortex of the Monkey in a Visual Memory Task,” *Journal of Neuroscience* 2, 361–375.

Fuster, Joaquin M. (1995) *Memory in the Cerebral Cortex. An Empirical Approach to Neural Networks in the Human and Nonhuman Primate*, MIT Press, Cambridge, MA.

Gazzaniga, Michael S., Richard B. Ivry and George R. Mangun (2002) *Cognitive Neuroscience: The Biology of the Mind*, 2nd ed., W. W. Norton & Company, New York.

Harris, Zellig S. (1951) *Structural Linguistics*, University of Chicago Press, Chicago.

Harris, Zellig S. (1952) “Discourse Analysis,” *Language* 28, 1–30.

Hasbrooke, Ronald E. and Christine Chiarello (1998) “Bihemispheric Processing of Redundant Bilateral Lexical Information,” *Neuropsychology* 12, 78–94.

Hebb, Donald O. (1949) *The Organization of Behavior: A Neuropsychological Theory*, John Wiley, New York.

Hobson, Allan J. (1999) *Ishiki to Nou* (Consciousness and Brain), Tuttle-Mory Agency, Tokyo.

Hopfield, John J. (1995) “Pattern Recognition Computation Using Action Potential Timing for Stimulus Representation,” *Nature* 376, 33–36.

Hoya, Tetsuya (2003) “On the Capability in Accommodating New Classes Within Probabilistic Neural Networks,” *IEEE Transactions on Neural Networks* 14, 450–453.

Hoya, Tetsuya (2004) “Self-Organising Associative Kernel Memory for Multi-Domain Pattern Classification,” *Proceedings of the IFAC Workshop on Adaptation*

and Learning in Control and Signal Processing (ALCOSP2004), 735–740.

Hoya, Tetsuya (2005) *Artificial Mind System—Kernel Memory Approach*, Springer, Heidelberg.

Hoya, Tetsuya and Noriko Toyoda-Akiho (2006) "Artificial Intelligence and Language Acquisition—An Example of A New Approach—Solution to the 'WUG'-Test Interpreted within the Artificial Mind System Context," *Proceedings of the 8th Annual International Conference of Japanese Society for Language Sciences (JSLS2006)*, 169–174.

Hoya, Tetsuya and Yoshikazu Washizawa (2007) "Simultaneous Pattern Classification and Multidomain Association Using Self-Structuring Kernel Memory Networks," *IEEE Transactions on Neural Networks* 18, 732–744.

Hubel, David (1995) *Eye, Brain, and Vision*, 2nd ed., Scientific American Library, New York.

Kinoshita, Jun (1996) *Neural-Net to Gengobunpo* (Neural Networks and Language Syntax), KikuChu Insatsu, Iwate.

Krause, Christina M., Pirjo Korpilahti, Bodil Porn, Joakim Jantti and Heikki A. Lang (1998) "Automatic Auditory Word Perception as Measured by 40Hz EEG Responses," *Electroencephalography and Clinical Neurophysiology* 107, 84–87.

Lashley, Karl S. (1951) "The Problem of Serial Order in Behavior," *Cerebral Mechanisms in Behavior*, The Hixxon Symposium, ed. by Lloyd A. Jeffres, 112–136, Wiley, New York.

Lichtheim, Ludwig (1885) "On Aphasia," *Brain* 7, 433–484.

Macwhinney, Brian (2001) "Emergentist Approaches to Language," *Frequency and the Emergence of Linguistic Structure*, ed. by John Bybee and Paul Hopper, 449–470, John Benjamins, Amsterdam.

Marcus, Gary F. (2001) *The Algebraic Mind: Integrating Connectionism and Cognitive Science*, MIT Press, Cambridge, MA.

McCulloch, Warren S. and Walter H. Pitts (1943) "A Logical Calculus of Ideas Immanent in Nervous Activity," *Bulletin of Mathematical Biophysics* 5, 115–133.

Mesulam, Marsel M. (1990) "Large-Scale Neurocognitive Networks and Distributed Processing for Attention, Language, and Memory," *Annals of Neurology* 28, 597–613.

Milner, Peter M. (1974) "A Model for Visual Shape Recognition," *Psychological Review* 81, 521–535.

Moody, John E. and Christian J. Darken (1989) "Learning Algorithms and Networks of Neurons," *The Computing Neurons*, ed. by Richard Durbin, Christopher Miall and Graeme Michison, 35–53, Addison-Wesley, Reading.

Näätänen, Risto, Anne Lehtokoski, Mietta Lennes, Marie Cheour, Minna Huotilainen, Antti Iivonen, Martti Vainio, Paavo Alku, Risto J. Ilmoniemi, Aavo Luuk, Juri Allik, Janne Sinkkonen and Kimmo Alho (1997) "Language-Specific Phoneme Representations Revealed by Electric and Magnetic Brain Responses," *Nature* 385, 432–434.

Otake, Yoshio (1995) "Onsei-No-Chikaku (Perception of Speech Sound)," *Ninchigengogaku* 3 (Cognitive Psychology 3), ed. by Yukio Otsu, 131–144, University

of Tokyo Press, Tokyo.
Palm, Günther (1981) "Towards a Theory of Cell Assemblies," *Biology and Cybernetics* 39, 181–194.
Palm, Günther (1982) *Neural Assemblies*, Springer, Berlin.
Pandya, D. N. and E. H. Yeterian (1985) "Architecture and Connections of Cortical Assocation Areas," *Cerebral Cortex*, ed. by Alan Peters and Edward G. Jones, 4, 3–61, Plenum, London.
Petersen, Steven and Julie A. Fiez (1993) "The Processing of Single Words Studied with Positron Emission Tomography," *Annual Review in Neuroscience* 16, 509–530.
Pickering, Martin J. and Holly P. Branigan (1999) "Syntactic Priming in Language Production," *Trends in Cognitive Sciences* 3, 136–141.
Pinker, Steven (1999) *Words and Rules: The Ingredients of Language*, Perennial, New York.
Pulvermüller, Friedemann and Bettina Mohr (1996) "The Concept of Transcortical Cell Assemblies: A Key to the Understanding of Cortical Lateralization and Interhemispheric Interaction," *Neuroscience and Biobehavioral Reviews* 20, 557–566.
Pulvermüller, Friedemann, Niels Birbaumer, Werner Lutzenberger and Bettina Mohr (1997) "High-frequency Brain Activity: Its Possible Role in Attention, Perception and Language Processing," *Progress in Neurobiology* 52, 427–445.
Pulvermüller, Friedemann (1999) "Words in the Brain's Language," *Behavioral and Brain Sciences* 22, 253–336.
Pulvermüller, Friedemann (2001) "Brain Reflections of Words and Their Meaning," *Trends in Cognitive Neurosciences* 5, 517–524.
Reichardt, Werner and Deepak Varju (1959) "Übertragungseigenschaften im Auswertesystem für das Bewegungssehen (Transmission Characteristics in the Evaluation System for Seeing Movement)," *Zeitschrift für Naturforschung* 14, 674–689.
Rosenblatt, Frank (1959) "Two Theorems of Statistical Separability in the Perceptron," *Mechanisation of Thought Processes: Proceedings of A Symposium Held at the National Physical Laboratory*, ed. by Oliver Selfridge, 1, 421–456, HM Stationery Office, London.
Rumelhart, David E., Geoffrey E. Hinton and Ronald J. Williams (1986) "Learning Internal Representations by Backpropagation," *Parallel Distributed Processing: Explorations in the Microstructure of Cognition Vol. 1*, ed. by David E. Rumelhart and James L. McClelland, 318–362, MIT Press, Cambridge, MA.
Schnelle, H. (1996) "Approaches to Computational Brain Theories of Language—A Review of Recent Proposals," *Theoretical Linguistics* 22, 49–104.
Shtyrov, Yury, Teija Kujala, Satu Palva, Risto J. Ilmoniemi and Risto Näätänen (2000) "Discrimination of Speech and of Complex Nonspeech Sounds of Different Temporal Structure in the Left and Right Cerebral Hemispheres," *NeuroImage* 12, 657–663.
Stork, David G. (1989) "Is Backpropagation Biologically Plausible?" *Proceedings of*

the International Joint Conference on Neural Networks (IJCNN-89) 2, 241–246.
Tallon-Baudry, Catherine and Olivier Bertrand (1999) "Oscillatory Gamma Activity in Humans and Its Role in Object Representation," *Trends in Cognitive Sciences* 3, 151–161.
Tesnière, Lucien (1953) *Esquisse d'Une Syntax Structurale* (Essentials of Syntax Structure), Klincksieck, Paris.
Tesnière, Lucien (1959) *Elements de Syntaxe Structurale* (Elements of Syntax Structure), Klincksieck, Paris.
Vapnik, Vladimir, N. (1996) *The Nature of Statistical Learning Theory*, Springer, New York.
von der Malsburg, Christoph (1995) "Binding in Models of Perception and Brain Function," *Current Opinions in Neurobiology* 5, 520–526.
Wernicke, Carl (1874) *Der Apharasische Symptomencomplex. Eine Psychologische Studie auf Anatomischer Basis* (The Aphasic Syndrome: A Psychological Study on an Anatomical Basis), Kohn and Weigert, Breslau.
Willshaw, David J., Peter O. Buneman and Christopher H. Longuet-Higgins (1969) "Non-holographic Associative Memory," *Nature* 222, 960–962.
Young, Malcolm P., Jack. W. Scannel and Gully Burns (1995) *The Analysis of Cortical Connectivity*, Springer, Heidelberg.
Zaidel, Eran (1976) "Auditory Vocabulary of the Right Hemisphere Following Brain Bisection or Hemideocortication," *Cortex* 12, 191–211.
Zaidel, Eran (1985) "Language in the Right Hemisphere," *The Dual Brain*, ed. by D. F. Benson and Eran Zaidel, 205–231, Guilford, New York.
Zatorre, Robert J., Alan C. Evans, Ernst Meyer and Albert Gjedde (1992) "Lateralization of Phonetic and Pitch Discrimination in Speech Processing," *Science* 256, 846–849.

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