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COMPOSITIONALITY

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NON-SYMBOLIC COMPOSITIONAL REPRESENTATION AND ITS NEURONAL FOUNDATION: TOWARDS AN EMULATIVE SEMANTICS

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31.1 COMPOSITIONALITY AND CONSTITUENCY

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Throughout its history the principle of compositionality, a widely acknowledged cornerstone for any theory of meaning, has been closely associated with what one might call the principle of semantic constituency. The latter characterizes the subclass of the symbolic theories of meaning. In this chapter a neurobiologically motivated theory of meaning as internal representation will be developed that holds on to the principle of compositionality, but negates the principle of semantic constituency. It is in this sense non-symbolic. The approach builds on neurobiological findings regarding topologically structured cortical feature maps and the mechanism of object-related binding by neuronal synchronization. It incorporates the Gestalt principles of psychology and is implemented by recurrent neural networks. The semantics to be developed is structural analogous—yes, in fact isomorphic—to some variant of model-theoretical semantics, which likewise is compositional and non-symbolic. However, unlike standard

model-theoretical semantics, it regards meanings as set-theoretical constructions not of denotations, but of their neural counterparts or, as we will say, their emulations. The semantics to be developed is a neuro-emulative model-theoretical semantics of a first-order language.

The association between the two principles can already be found in what is often regarded as Frege's classical formulation of compositionality:

> With a few syllables [language] can express an incalculable number of thoughts .... This would be impossible, were we not able to distinguish parts in the thoughts corresponding to the parts of a sentence, so that the structure of the sentence serves as the image of the structure of the thought. (Frege, 1923/1976: 55)

The compositionality of meaning today is typically captured by the following principle (Hodges, 2001; Werning, 2004):

Principle 1 (Compositionality of meaning). *The meaning of a complex term is a syntax-dependent function of the meanings of its syntactic parts.*

If one identifies Fregean thoughts with the meanings of sentences, regards sentences as instances or evaluations of complex terms and specifies the parts of sentences as syntactic parts and their structure as a syntactic structure, the last subclause of the quotation can indeed be regarded as echoing the modern principle of compositionality. One only has to presume that Frege, when he spoke of an image, had in mind a homomorphism between two algebraic structures: the syntactic structure of terms and the semantic structure of meanings.

However, the preceding subclause expresses an idea that is in fact distinct therefrom. It postulates a correspondence relation between the part–whole relation in the linguistic domain and some part–whole relation on the level of meanings. One might capture this idea as the principle of semantic constituency:

Principle 2 (Semantic constituency). *There is a semantic part–whole relation on the set of meanings such that for every two terms, if the one is a syntactic part of the other, then the meaning of the former is a semantic part of the meaning of the latter.*

In accordance with a widely used terminology, for a language the *syntactic structure of terms*—sometimes also called term algebra or simply syntax—is regarded as a pair $\langle T, \Sigma_T \rangle$. Here T is the set of terms of the language and Σ_T is a finite set of syntactic operations that reflect syntactic rules of the language. Each syntactic operation $\sigma \in \Sigma_T$ is a partial function from some Cartesian product T^n of the set of terms into the set of terms.

A term s is called an *immediate syntactic part* of a term t just in case there is a syntactic operation σ that may render t as value when s is one of its arguments, in other words: $t = \sigma(\ldots, s, \ldots)$. Any term s is recursively defined to be a *syntactic part* of a term t—in symbols $s \sqsubseteq_T t$—just in case s is either identical to t, an immediate syntactic part of t or an immediate syntactic part of some syntactic part of t. A term is called atomic if

it does not have any syntactic parts but itself. It is assumed that there are only finitely many atomic terms.

For the language, the set of meanings M is the range of some meaning function μ defined on T (or a subset thereof). The compositionality condition now comes down to the claim that M can be supplemented by a set of semantic operations Σ_M such that μ is a homomorphism from the syntax $\langle T, \Sigma_T \rangle$ into the structure $\langle M, \Sigma_M \rangle$, called the semantics or semantic structure of the language. In other words:

Definition 1 (Formal Compositionality). *Given a language with the syntax $\langle T, \Sigma_T \rangle$, a meaning function $\mu : T \to M$ is called compositional just in case, for every n-ary syntactic operation $\sigma \in \Sigma_T$ and any sequence of terms $t_1, .., t_n$ in the domain of σ, there is a partial function m_σ defined on M^n such that*

$$\mu(\sigma(t_1, .., t_n)) = m_\sigma(\mu(t_1), \ldots, \mu(t_n)).$$

A semantics induced by a compositional meaning function will be called a compositional semantics of the language.

The principle of semantic constituency makes a statement about the correspondence of two part–whole relations. The weakest conditions one may set upon a part–whole relation $\sqsubseteq$ is that it be reflexive, transitive, and anti-symmetric:

Definition 2 (Part–whole Relation). *A relation $\sqsubseteq$ defined on a set X is called a part–whole relation on X just in case, for all $x, y, z \in X$ the following holds:*[1]

(i) $x \sqsubseteq x$ *(reflexivity).*
(ii) $x \sqsubseteq y \land y \sqsubseteq x \to x = y$ *(anti-symmetry).*
(iii) $x \sqsubseteq y \land y \sqsubseteq z \to x \sqsubseteq z$ *(transitivity).*

The notion of a part–whole relation can be strengthened in various ways. One may, for example, assume that parts are always co-tokened with their wholes (McLaughlin, 1993) or that parts are spatially contained in the respective wholes. However, our definition is unanimously accepted as a minimal condition on parts and moreover consistent with the definition of a syntactic part.

31.2 SYMBOLIC AND NON-SYMBOLIC THEORIES OF MEANING

As we will illustrate by two examples below, the principle of semantic constituency is the hallmark of all symbolic theories of meaning. These theories regard meanings themselves as symbols. They can be characterized as follows:

[1] The definition of a proper part negates the reflexivity condition.

Definition 3 (Symbolic Semantics). *Given a language with the syntax $\langle T, \Sigma_T \rangle$, a thereon defined syntactic part–whole relation $\sqsubseteq_T$ and a meaning function $\mu : T \to M$, then its semantics $\langle M, \Sigma_M \rangle$ is symbolic if and only if there is a part–whole relation $\sqsubseteq_M$ defined on M such that for all terms $s, t \in T$ the following holds:*

$$s \sqsubseteq_T t \to \mu(s) \sqsubseteq_M \mu(t).$$

In other words, what's common to all symbolic theories of meaning is that the part–whole structure on the syntactic level is mirrored on the semantic level. The best known example for a symbolic theory of meaning is Fodor's (1975, 2008) Language of Thought. Here meanings are identified with mental concepts and modelled as entries on the tape of a Turing computer. From a finite alphabet of primitive concepts, say {DOG, CAT, BARKS, MEOWS, FIDO, TOM, NOT, . . .}, complex concepts are built as sequences or strings. The semantic part–whole relation is identified with the relation of being a substring. Since *LOT* is a symbolic theory of meaning, it is guaranteed that whenever a syntactically complex expression contains a less complex one as a syntactic part, as happens to be the case with the sentences *Fido is not a dog* and *Fido is a dog*, the meaning of the syntactic part, that is DOG FIDO is a substring of the meaning of the whole, NOT DOG FIDO.[2]

However, a computational or serial format is not required for a theory of meaning to be symbolic. Motivated by the many shortcomings the *LOT* approach was accused of when the aim is to provide a psychologically and neurobiologically realistic theory of representation (see Horgan and Tienson, 1996; Horgan, this volume), connectionists have proposed so-called Vector Symbolic Architectures (VSAs) (see Smolensky, 1995*b*; Plate, 2003; Stewart and Eliasmith, this volume): meanings or representations are conceived of as vectors rendering a certain pattern of activity in a connectionist network. In contrast to conventional parallel distributed processing architectures, representations in VSA networks can realize part–whole relations and thus do provide a symbolic account of meaning.

VSAs employ operations of binding $\otimes$ and merging $\oplus$ and so allow meanings of complex terms to be generated from the meanings of their syntactic parts, viz. by the combination of role and filler vectors. Given the sentence *Mary loves John* with a certain underlying syntactic structure, its meaning would, for example, be identified with a vector **p** generated in the following way:

$$\mu(\text{Mary loves John}) = \mathbf{p} \tag{31.1}$$

$$= \mathbf{event} \otimes \mathbf{loves} \oplus \mathbf{agent} \otimes \mathbf{mary} \oplus \mathbf{patient} \otimes \mathbf{john}. \tag{31.2}$$

The role vectors **event**, **agent**, and **patient** stand for certain semantic roles. These are bound to the filler vectors **mary**, **loves**, and **john**, which are identified with the meanings of the words *Mary*, *loves*, and *John*. The operations of binding and merging are recursively applicable. VSAs can be made compositional by choosing role and filler

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[2] We assume that the language of thought is structurally analogous to a first-order language or some extension thereof, so that the two thoughts have the logical form *Fa* and, respectively, ¬*Fa*.

vectors such that the semantic structure is a homomorphic image of the syntactic structure of the language. In early examples of VSAs (Smolensky, 1995*b*) tensor multiplication was used for binding and vector addition for merging. This led to a dimensional explosion of the network and had a number of technical disadvantages. In the more recent holographic approach of Plate and Stewart and Eliasmith, circular convolution is used for binding. Here the N components of a vector $\mathbf{u}$ resulting from a circular convolution of a vector $\mathbf{v}$ with a vector $\mathbf{w}$ are given as: $u_i = \sum_{j=1}^{N} v_i w_{(i-j) \bmod N}$. This keeps dimensions low and more importantly allows an inverse $\mathbf{z} = inv(\mathbf{u})$ with $z_i = u_{(N-i) \bmod N}$ to be defined. This gives us an operation of unbinding. Any filler vector is now approximately recoverable. For the above example one would get:

$$\mathbf{p} \otimes inv(\mathbf{agent}) \approx \mathbf{mary}. \qquad (31.3)$$

In this approach the semantic part-whole relation is identified with the relation of being recoverable by an algorithm of unbinding. VSA semantics with an operation of unbinding is not only compositional, but also symbolic.

To see that a compositional semantics need not be symbolic, let us turn to standard model-theoretical semantics, which is a paradigmatic example for a compositional semantics. The details of such a semantics are given elsewhere (see Partee, ter Meulen, and Wall, 1990; Kracht, this volume). For our purposes it suffices to mention that in standard model-theoretical semantics the meaning of a sentence ϕ is the set of its models. Now, the sentence ϕ is a syntactic part of $\neg \phi$, which in turn is a syntactic part of $\neg \neg \phi$. If standard model theoretical semantics were symbolic, these part–whole relations should be reflected on the semantic level in the following way:

$$\mu(\phi) \sqsubseteq_M \mu(\neg \phi) \sqsubseteq_M \mu(\neg \neg \phi). \qquad (31.4)$$

However, the double negation $\neg \neg \phi$ has exactly the same models as ϕ and consequently exactly the same meaning. Therefore:

$$\mu(\phi) \sqsubseteq_M \mu(\neg \phi) \sqsubseteq_M \mu(\phi). \qquad (31.5)$$

Using the anti-symmetry of the part–whole relation we derive the contradiction:

$$\mu(\phi) = \mu(\neg \phi). \qquad (31.6)$$

For model-theoretical semantics there is no semantic part–whole relation that fulfils the principle of semantic constituency. We have thus shown that the principle of compositionality and the principle of semantic constituency logically fall apart. This is so even though many compositional theories of meaning are in fact symbolic. The model-theoretic counterexample should be remembered when we develop our neuro-emulative semantics, since both are structurally analogous to each other.

Unlike the language of thought or vector symbolic architectures, model-theoretical semantics is merely denotational. It does not imply anything about the structures of the mind or the underlying neural mechanisms that enable us to produce and comprehend meaningful expressions. For many explanatory purposes—the learning, production, or comprehension of language, the underlying biological resources, their evolution

and development and eventual disorders—a purely denotational account of meaning remains vacuous. In this chapter I will therefore appeal to a mentally or neurally realistic view of meaning. It characterizes the triangle between language, mind, and world as follows: linguistic expressions are expressions of meaning. Those meanings are to be identified with mental or otherwise internal representations. An internal representation *qua* being a representation essentially has an external content. This external content in turn is responsible for the fact that the expression in question has the denotation it has. The relation between a mental representation and its content is some form of causal-informational covariation (Fodor, 1992). This view is captured by our last semantic principle:[3]

Principle 3 (Content covariation). *An expression has the denotation it has because the meaning it expresses is an internal representation that reliably co-varies with a content that is identical to the expression's denotation.*

In what is to come we will do the following: for a given first-order language we will introduce a neural structure that will then be identified with an internal semantic structure. The neural structure is derived from an algebraic description of the topology and dynamics of oscillatory networks, a member of the recurrent connectionist network family. The topology of those networks closely follows the topological organization of neurobiologically well studied cortical feature maps for various attributes such us colour, orientation, direction of movement, etc. Feature maps of this kind are ubiquitous throughout the sensory cortices of the brains of humans and many other mammals. The dynamics of oscillatory networks is designed to reflect the well-studied mechanisms of object-related neural synchronization (see Maye and Engel, this volume). We will demonstrate that the neural structure provides a compositional semantics of the language. Compositionality of meaning will hence be achieved. It will become obvious that this semantics is non-symbolic in the sense defined above. The principle of semantic constituency is negated. We will also show that the elements of the neural structure are internal representations that reliably co-vary with external contents. These external contents are identical with the standard model-theoretical denotations for the language. The covariation with content is achieved. It will finally become clear that the covariation is one-to-one such that the neural structure can be regarded as isomorphic to the external denotational structure. These results justify us to call the neural structure an emulative semantics. This is to say that each denotation of an expression in our language has a potential counterpart neural state that co-varies with the denotation. An oscillatory network thus generates an algebraic emulation of what it represents. The neural structure is a compositional, non-symbolic, emulative semantics of a first-order language.

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[3] Philosophically, the principle may strike one as over simplifying rather complex dependency relation between contents and denotations. It certainly needs some fine-tuning. Its impact and elegance for the purposes of this text will, however, become clear below. I conceive of denotation in a broad sense as modal denotation. The denotation of a sentence might, for example, be identified with a proposition (eventually modelled as a set of models or possible worlds). See Werning (2011).

31.3 Cortical feature maps, neuronal synchronization, and the Gestalt principles

The architecture of oscillatory networks, which lays the ground for our emulative semantics, is motivated by empirical findings that regard the existence of topologically structured cortical feature maps, the neural mechanism of object-relative synchronization, and the Gestalt principles of perception. Given that these findings justify the biologically and psychologically adequateness of our network model, I will briefly recapitulate the findings here.

31.3.1 Feature maps

For many attributes (colour, orientation, direction, size, etc.) involved in the course of visual processing one can anatomically identify so-called neuronal feature maps (Hubel and Wiesel, 1968). These are parts of the cortex that exhibit a two-fold topological organization: a receptor topology and a feature topology. Each (pyramidal) neuron x of the feature map has a specific receptive field $r(x)$ on the receptor (in vision, the retina) and a specific feature selectivity $f(x)$. The receptive field is a geometrically convex region on the receptor. The feature selectivity is characterized by a convex region in the attribute space associated with the feature map. A specific neuron in an orientation map, for instance, will fire if a stimulus object, say a bar projected on the retina, is located in the receptive field of the neuron and its orientation has a value in an interval of angles for which the neuron is selective. By speaking of a receptor topology we mean that the synaptic connectivity of neurons within a feature map reflects the geometry of the receptor. The density of synaptic connectivity introduces a topology among the neurons of a feature map. A neuron counts as closer to a reference neuron as compared to a third neuron if the connectivity density between the first and the reference neuron is greater than that between the third and the reference neuron. In humans and many other mammals this connectivity topology is roughly congruent to the topography of the feature maps given by the actual physical distances between neurons (see Fig. 31.1). In the case of vision we say that those feature maps are retinotopic. With some idealizations we can formulate the principle that having a receptive field r is a topologically continuous mapping from the connectivity topology of the feature map into the geometry of the receptor: given a certain neuron in the feature map, all neurons close to it have receptive fields that are close to the receptive field of the given neuron. A second topological principle holds for the feature selectivities of the neurons in a feature map: having a certain feature selectivity f is a topologically continuous mapping from the connectivity topology of the feature map into the topology of the attribute space. Or in other words: given a certain
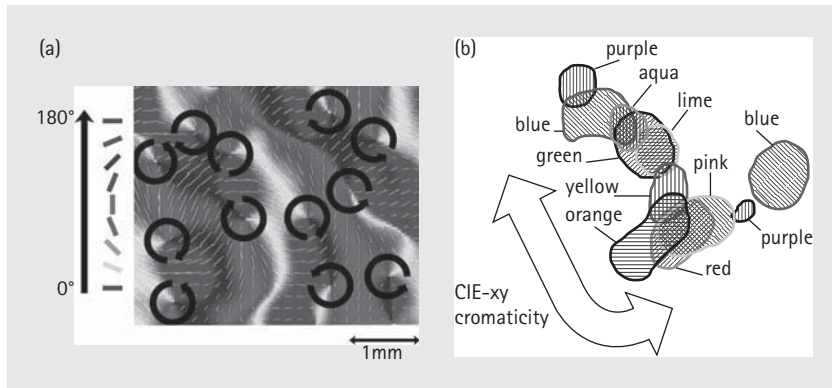
FIGURE 31.1 Cortical feature maps. (a) Fragment of the neural feature map for the attribute orientation of cat primary visual cortex (adapted from Shmuel and Vald, 2000). The arrows indicate the polar topology of the orientation values represented within each hypercolumn. Hypercolumns are arranged in a retinotopic topology. (b) Colour band (*ca.* 1 mm^2) from the thin stripes of macaque secondary visual cortex (adapted from Xiao et al., 2003). The values of the attribute colour are arranged in a topology that follows the similarity of hue as defined by the Commission Internationale de l'Eclairages (xy-cromaticity). The topology among the various colour bands of the thin stripes is retinotopic. Both in (a) and (b) the synaptic connectedness is reflected by the cortical topography.

neuron in the feature map, all neurons close to it have feature selectivities that are similar to the feature selectivity of the given neuron.[4] Fig. 31.1 shows fragments of cortical feature maps for the attributes orientation and colour. In the orientation map (Fig. 31.1a) one finds pinwheel-like structures for particular receptive fields. These structures are called hypercolumns. Each hypercolumn typically has an extent of about 1 mm^2. The receptive fields of overlapping hypercolumns overlap. Within each hypercolumn, neurons for the entire spectrum of values of the attribute, that is angles of orientation, fan out around a pin-wheel centre realizing a polar topology. Neurons of a hypercolumn with a tuning for the same attribute value form a so-called minicolumn. The colour map in the thin stripes of the secondary visual cortex (Fig. 31.1b), in contrast, shows a linear topology. The neurons of neighbouring stripes have neighbouring or overlapping receptive fields. More than 80 so organized cortical areas are experimentally known to be involved in the visual processing of the monkey (Felleman and van Essen, 1991). It should be noted that cortical areas with a feature topology can also be found in higher cortical areas involved in vision, whereas the receptor topology seems to be characteristic only for the cortical areas carrying out early visual processes. Cortical maps with a

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[4] Having defined a metric d_c on the connectivity topology, a metric d_r for distances between regions on the receptor, and a metric d_f for distances between regions in the attribute space, the receptor and feature topology of feature maps can be formally characterized as follows. Receptor topology: for any choice of $\epsilon > 0$ there is a $\delta > 0$ such that for all neurons x, y of the feature map with $d_c(x, y) < \delta$ it holds that $d_r(r(x), r(y)) < \epsilon$. Feature topology: for any choice of $\epsilon > 0$ there is a $\delta > 0$ such that for all neurons x, y of the feature map with $d_c(x, y) < \delta$ it holds that $d_f(f(x), f(y)) < \epsilon$.

feature topology can also be found in the auditory and somatosensory cortices, where they exhibit tonotopic (Bendor and Wang, 2005) or somatotopic topologies (DiCarlo and Johnson, 2000).

31.3.2 Neural synchronization

The fact that feature values which belong to different attributes, but may be properties of the same stimulus object are processed in distinct regions of the cortex, poses the problem of how this information is integrated in an object-specific way. How can it be that the horizontality and the redness of a red horizontal bar are represented in distinct regions of cortex, but are still part of the representation of one and the same object? This is the binding problem in neuroscience (Treisman, 1996).

A prominent and experimentally well supported solution postulates neuronal synchronization as a mechanism for binding (von der Malsburg, 1981; Gray et al., 1989; Maye and Engel, this volume): neurons that are selective for different properties show synchronous activation when the properties indicated are instantiated by the same object in the perceptual field; otherwise they are firing asynchronously. Synchrony, therefore, might be regarded as fulfilling the task of binding together various property representations in order to form the representation of an object as having these properties. Object-specific synchrony has been measured within minicolumns, within and across hypercolumns, across different feature maps, even across the two hemispheres and on a global scale (for a review see Singer, 1999).

31.3.3 The Gestalt principles

The rules that govern the constitution of objects in perception—that is the rules according to which we perceive a group of stimulus elements as one object—have been studied in perceptual psychology. These studies led to the formulation of the Gestalt principles (Wertheimer, 1924/1950). Fig. 31.2a illustrates the Gestalt principle of similarity of colour: all things being equal, the more similar neighbouring elements of the stimulus are with respect to colour, the more likely they are to be perceptually grouped together into one object. Fig. 31.2b gives an analogous example for the Gestalt principle of similarity of orientation. Those principles are instances of a more general principle that can be expressed as follows: there are a number of attributes (colour, orientation, size, gradient, direction, etc.) that govern the perceptual grouping of stimulus elements into objects such that, all things being equal, the more similar the values of neighbouring stimulus elements are with respect to those attributes, the more likely those elements are perceptually grouped into one object. These Gestalt principles are formulated as *ceteris paribus* rules (see Palmer, 1999, for review). Trade-offs between similarities with respect to various attributes may occur.
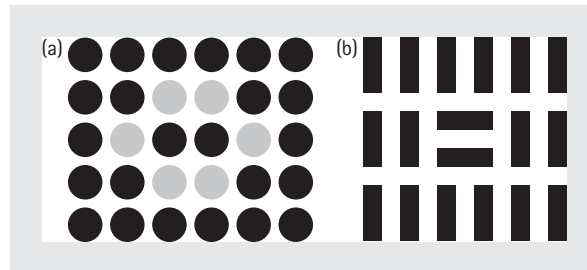
FIGURE 31.2 Illustration of Gestalt principles. (a) Similarity of colour. Neighbouring stimulus elements of light grey colour are perceptually grouped into one object. (b) Similarity of orientation. A square made up of two vertical bars pops out as one object.

31.4 OSCILLATORY NETWORKS

The neurobiological facts on neuronal feature maps and object-relative neural synchronization together with the psychological principles of Gestalt perception allow us to regard oscillatory networks (see Fig. 31.3) as a plausible model of informational processes in the visual cortex.

Oscillatory networks are recurrent neural networks whose basic units are oscillators each consisting of an excitatory and inhibitory node. The oscillators are arranged on a three-dimensional grid forming a module (Fig. 31.3c) that is associated with a certain attribute (colour, orientation, etc.). Each oscillator is first characterized by a receptive field whose coordinates are given relative to the two dimensional XY-plane. It is secondly characterized by its feature selectivity, represented on the Z-axis. Both the receptor and the feature topology of cortical feature maps are honoured by the network topology.

The *Gestalt* principles are implemented in oscillatory networks by the following mechanism: oscillators with neighbouring receptive fields and similar feature selectivities tend to synchronize (light shading), whereas oscillators with neighbouring receptive fields and different feature selectivities tend to desynchronize. As a consequence, oscillators selective for proximal stimulus elements with like properties tend to form a synchronous oscillation when stimulated simultaneously. This oscillation can be regarded as one object representation. In contrast, inputs that contain proximal elements with unlike properties tend to cause anti-synchronous oscillations, that is different object representations. This result is in line with the findings of object-related neural synchronization.

In our model a single oscillator (Fig. 31.3a) consists of two mutually coupled excitatory and inhibitory nodes. They are assigned the variables x and y, which statistically represent the electrical discharge behaviour of a minicolumn of a cortical feature map (typically about 80 to 120 biological cells).
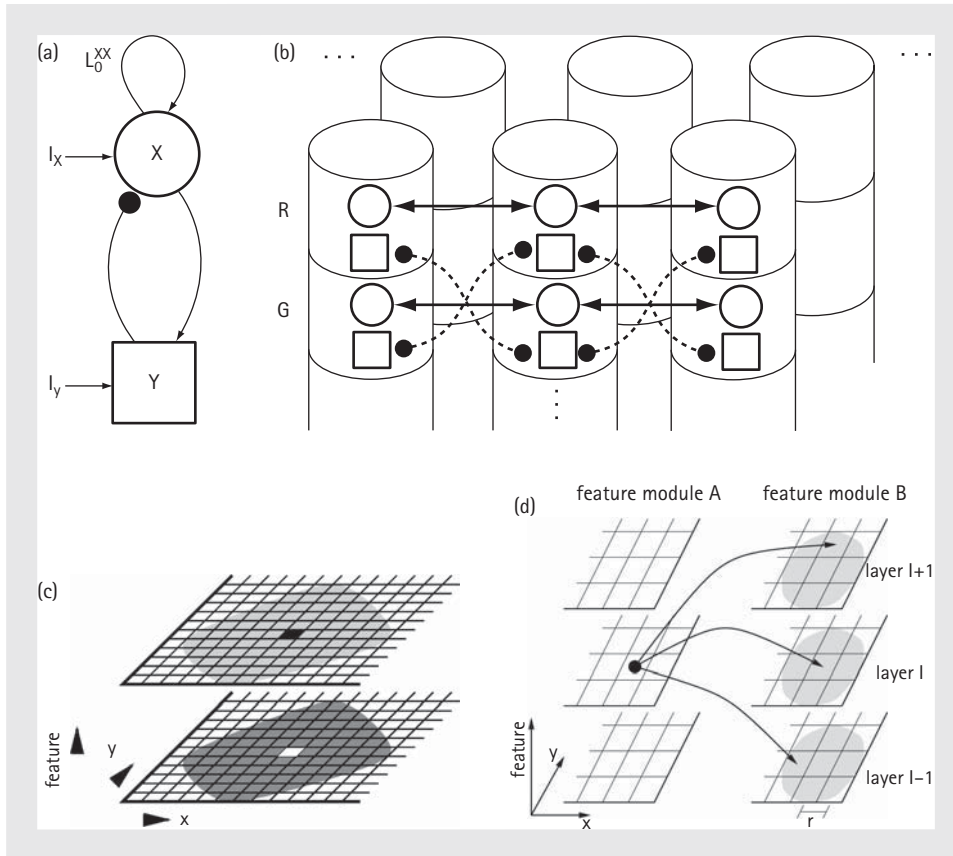
FIGURE 31.3 Oscillatory network. (a) A single oscillator consists of an excitatory (x) and an inhibitory (y) node. Each node represents the average activity of a cluster of biological cells. L_0^{xx} describes the self-excitation of the excitatory neuron. I_x and I_y amounts to external input. (b) Synchronizing connections (solid) are realized by mutually excitatory connections between the excitatory nodes and hold between oscillators within one layer. Desynchronizing connections (dotted) are realized by mutually inhibitory connections between the inhibitory nodes and hold between different layers. 'R' and 'G' denote the red and green channel. The cylinder segments correspond to minicolumns, whole cylinders to hypercolumns. (c) A module for a single feature dimension (e.g. colour) consists of a three-dimensional topology of oscillators. There is one layer per feature and each layer is arranged to reflect a two-dimensional retinotopic structure. The shaded circles visualize the range of synchronizing (light grey) and desynchronizing (dark grey) connections of an oscillator in the top layer (black pixel). (d) Two coupled feature modules are shown schematically. The single oscillator in module *A* has connections to all oscillators in the shaded region of module *B*. This schema is applied to all other oscillators and feature modules.

Source: Reprinted from Werning (2005*b*) and Maye (2004).

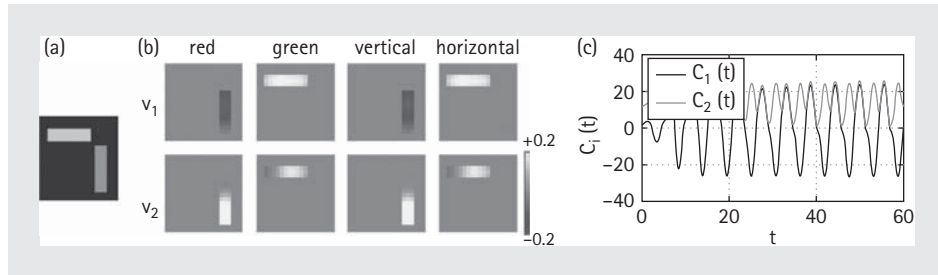**FIGURE 31.4** (a) Stimulus: one vertical red bar and one horizontal green bar. It was presented to a network with $32 \times 32 \times 4$ oscillators. (b) The two stable eigenmodes. The eigenvectors v_1 and v_2 are shown each in one line. The four columns correspond to the four feature layers. Dark shading signifies negative, grey zero and light shading positive components. (c) The characteristic functions for the two eigenmodes.

Synchronizing (resp. de-synchronizing) connections between two oscillators are realized by mutually excitatory (inhibitory) connections between the excitatory (inhibitory) nodes of both oscillators (Fig. 31.3b). Feature modules for different feature dimensions, for example colour and orientation, can be combined by establishing synchronizing connections between oscillators of different modules in case they code for the same stimulus region (Fig. 31.3d).

Populations of recurrently coupled excitatory and inhibitory neurons can be found in the primary visual cortex. Here, excitatory (pyramidal) cells in layers 2 and 3 are tightly coupled to local inhibitory neurons in layers 2–6. If the number of excitatory and inhibitory biological cells is large enough, the dynamics of each oscillator can be statistically described by the temporal evolution of the variables x and y according to differential equations that describe limit-cycle oscillations (for an explicit mathematical description see Maye (2003), Maye and Werning (2004, 2007)).

Stimulated oscillatory networks characteristically show object-specific patterns of synchronized and de-synchronized oscillators within and across feature dimensions. In Fig. 31.4 the network dynamics for a stimulus consisting of a red vertical and a green horizontal bar is shown. Oscillators that represent properties of the same object synchronize, while oscillators that represent properties of different objects desynchronize. We observe that for each represented object a certain oscillation spreads through the network. The oscillation pertains only to oscillators that represent the properties of the object in question.

31.5 ALGEBRAIC NETWORK ANALYSIS

An oscillation function $x(t)$ of an oscillator is the activity of its excitatory node as a function of time during a time window $[0, T]$. Mathematically speaking, activity functions

can be conceived of as vectors in the Hilbert space $L_2[0, T]$ of functions that are square-integrable in the interval $[0, T]$. Thus, a precise measure of synchrony can be established and a powerful algebraic framework for the semantic interpretation of the network will be provided. The Hilbert space has the inner product

$$\langle x(t)|x'(t)\rangle = \int_0^T x(t)\, x'(t) dt. \tag{31.7}$$

The degree of synchrony between two oscillations lies between -1 and $+1$ and can now be defined as their normalized inner product

$$\Delta(x, x') = \frac{\langle x|x'\rangle}{\sqrt{\langle x|x\rangle \langle x'|x'\rangle}}. \tag{31.8}$$

The dynamics of complex systems is often governed by a few dominating states, the eigenmodes. The corresponding eigenvalues designate how much of the dynamics is accounted for by that mode. The two stable eigenmodes of a stimulated network are shown in Fig. 31.4b. The overall dynamics of the network is given by the Cartesian vector $\mathbf{x}(t) = (x_1(t), \ldots, x_k(t))^T$ that contains the excitatory activities of all k oscillators as components. The network state at any instant is considered as a superposition of the temporally constant, but spatially variant eigenvectors $\mathbf{v}_i$ weighted by the corresponding spatially invariant, but temporally evolving characteristic functions $c_i(t)$ of Fig. 31.4c:

$$\mathbf{x}(t) = \sum c_i(t)\mathbf{v}_i. \tag{31.9}$$

The eigenmodes, for any stimulus, can be ordered along their eigenvalues so that each eigenmode can be signified by a natural number i beginning with 1 for the strongest ($\mathbf{v}_i$ is the corresponding eigenvector).

The Hilbert space analysis allows us to interpret the dynamics of oscillatory networks in semantic terms. Since oscillation functions reliably co-vary with objects, they may be assigned to some of the individual terms a, b, ..., x, y, ... $\in$ Ind of a predicate language by the partial function

$$\alpha : \text{Ind} \rightarrow L_2[0, T]. \tag{31.10}$$

The sentence a $=$ b expresses a representational state of the system (i.e. the representation of the identity of the objects denoted by the individual terms a and b) to the degree the oscillation functions $\alpha(\text{a})$ and $\alpha(\text{b})$ of the system are synchronous. The degree to which a sentence ϕ expresses a representational state of the system, for any eigenmode i, can be measured by the value $d_i(\phi) \in [-1, +1]$. In case of identity sentences we have:

$$d_i(\text{a} = \text{b}) = \Delta(\alpha(\text{a}), \alpha(\text{b})). \tag{31.11}$$

When we take a closer look at the eigenvector of the first eigenmode in Fig. 31.4b, we see that most of the vector components are exactly zero (grey shading). However, few components in the greenness and the horizontality layers are positive (light shading) and few components in the redness and the verticality layers are negative (dark shading). We

may interpret this by saying that the first eigenmode represents two objects as distinct from one another. The representation of the first object is the characteristic function $+c_1(t)$ and the representation of the second object is its mirror image $-c_1(t)$ (Because of the normalization of the Δ-function, only the signs of the eigenvector components matter). These considerations justify the following evaluation of non-identity:[5]

$$d_i(\neg a = b) = \begin{cases} +1 \text{ if } d_i(a = b) = -1, \\ -1 \text{ if } d_i(a = b) > -1. \end{cases} \tag{31.12}$$

A great advantage of the eigenmode analysis is that object representations are no longer identified with the actual oscillatory behaviour of neurons, but with the eigenmode-relative characteristic functions. In this approach the representation of objects does not require strict synchronization of neural activity over long cortical distances, but tolerates a travelling phase change as it has been observed experimentally (Eckhorn et al., 2001) as well as in our network simulation.

Feature layers function as representations of properties and thus can be expressed by predicates $F_1, \ldots, F_p$, that is, to every predicate F a diagonal matrix $\beta(F) \in \{0,1\}^{k \times k}$ can be assigned such that, by multiplication with any eigenvector $\mathbf{v}_i$, the matrix renders the sub-vector of those components that belong to the feature layer expressed by F. To determine to which degree an oscillation function assigned to an individual constant a pertains to the feature layer assigned to a predicate F, we have to compute how synchronous it maximally is with one of the oscillations in the feature layer. We are, in other words, justified to evaluate the degree to which a predicative sentence Fa (read: 'a is F', e.g. 'This object is red') expresses a representational state of our system, with respect to the eigenmode i, in the following way (the f_j are the components of the vector $\mathbf{f}$):

$$d_i(Fa) = \max\{\Delta(\alpha(a), f_j) | \mathbf{f} = c_i(t)\beta(F)\mathbf{v}_i\}. \tag{31.13}$$

If one, furthermore, evaluates the conjunction of two sentences $\phi \wedge \psi$ by the minimum of the value of each conjunct, we may regard the first eigenvector $\mathbf{v}_1$ of the network dynamics resulting from the stimulus in Fig. 31.4a as a representation expressible by the sentence

This is a red vertical object and that is a green horizontal object.

We only have to assign the individual terms *this* (= a) and *that* (= b) to the oscillatory functions $-c_1(t)$ and $+c_1(t)$, respectively, and the predicates *red* (= R), *green* (= G), *vertical* (= V), and *horizontal* (= H) to the redness, greenness, verticality, and horizontality layers as their neuronal meanings. Simple computation then reveals:

$$d_1(Ra \wedge Va \wedge Gb \wedge Hb \wedge \neg a = b) = 1. \tag{31.14}$$

---

[5] The negation is sharp: it allows only -1 and $+1$ as values. In its definition we follow Gödel's (1932) intuitionist min-max-system. Double negation digitalizes the semantic value of the original sentence. The deeper reasons for this choice of the negation lie in systematic considerations concerning the envisaged calculus and the proof of completeness and compositionality theorems (Werning, 2005c).

Co-variation with content can always be achieved if the individual assignment α and the predicate assignment β are chosen to match the network's perceptual capabilities.

31.6 EIGENMODES AS ALTERNATIVE PERCEPTUAL POSSIBILITIES

So far I have concentrated on a single eigenmode only. The network, however, generates a multitude of eigenmodes. We tested the representational function of the different eigenmodes by presenting an obviously ambiguous stimulus to the network. The stimulus shown in Fig. 31.5a can be perceived as two red vertical bars or as one red vertical grating. It turned out that the network was able to disambiguate the stimulus by representing each of the two perceptual possibilities in a stable eigenmode of its own (see Fig. 31.5b).

Eigenmodes, thus, play a similar role for neuronal representation as possible worlds known from Lewis (1986) or Kripke (1980) play for semantics. Like possible worlds, eigenmodes do not interfere with each other because they are mutually orthogonal.

We now see that both of the two stable eigenmodes shown in Fig. 31.5b can be expressed by a disjunctive sentence if we semantically evaluate disjunction as follows:[6]

$$d(\phi \vee \psi, i) = \max\{d(\phi, i), d(\psi, i)\}, \tag{31.15}$$

for any sentences ϕ and ψ of $PL^=$ and any eigenmode i. Either of the two eigenmodes $i = 1, 2$ makes $d(\phi, i)$ assume the value $+1$ if ϕ is set to the following disjunctive sentence, which says that there is one red vertical object—denoted by a—or two red vertical objects—denoted by b and c:

$$(Ra \wedge Va) \vee (Rb \wedge Rc \wedge Vb \wedge Vc \wedge \neg b = c).$$

One only needs to make the following assignments of individual constants to oscillation functions:

$$\alpha(a) = +c_1(t), \; \alpha(b) = +c_2(t), \; \alpha(c) = -c_2(t).$$

---

[6] The choice of the maximum as the semantic evaluation of disjunction is the primary reason for me to prefer the Gödel system over alternative systems of many-valued logic. The reason is that it is the only continuous evaluation of disjunction, a so-called t-conorm, that always takes the value of one of the disjuncts as the value of the disjunction. Other continuous t-conorms would hence not allow us to treat eigenmodes as independent alternative possibilities. We would not be able to say that a certain disjunction is true because a possibility (i.e. an eigenmode) expressed by one of its disjuncts exists (see Werning, 2005c).
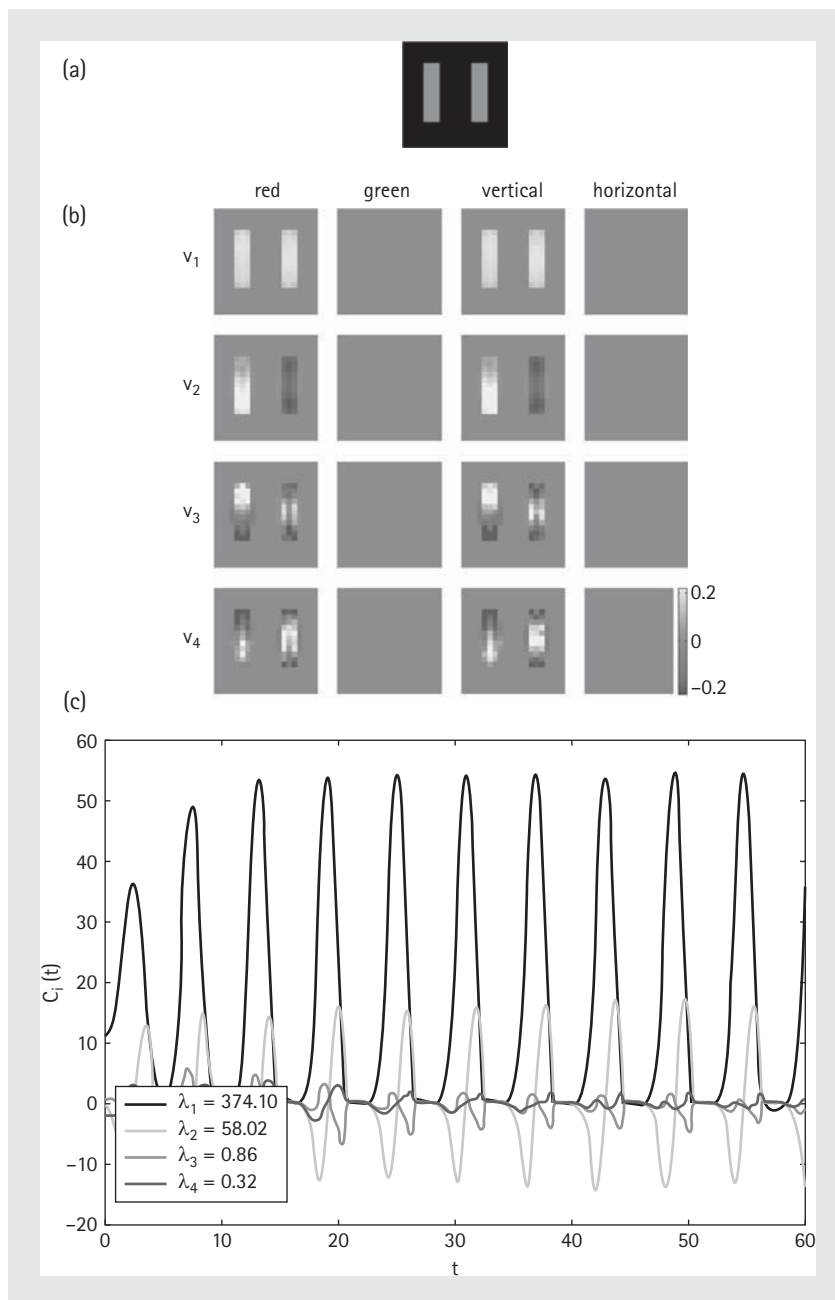
FIGURE 31.5 (a) Stimulus: two vertical red bars or one red vertical grating. (b) The eigenvectors $v_1, \ldots, v_4$ of the four eigenmodes $1, \ldots, 4$ with the largest eigenvalues are shown in one line. The first mode represents the stimulus as one red vertical object, while the second mode represents it as two red vertical objects. (c) The characteristic functions show the temporal evolution of the first four modes. Only the first two are non-decreasing and thus belong to stable eigenmodes. The left box gives the eigenvalues of the respective eigenmodes and their characteristic functions. The eigenvalues correspond to the relative contribution of the eigenmode to the variability of the overall network dynamics.

Source: Reprinted from Werning (2005*a*).

31.7 MAKING SYNTAX AND SEMANTICS EXPLICIT

We are leaving the heuristic approach now and turn to a formally explicit description of the neuronal semantics realized by oscillatory networks. Let the oscillatory network under consideration have k oscillators. The network dynamics is studied in the time window $[0, T]$. For any stable eigenmode $i \in \mathrm{N}$, it renders a determinate eigenvector $\mathbf{v}_i$, a characteristic function $c_i(t)$, and an eigenvalue λ_i after stimulation. The language to be considered is a monadic first-order predicate language with identity ($PL^=$). Let Ind be the set of individual terms and let Pred be the set of predicates. The alphabet of $PL^=$ furthermore contains the logical constants $\wedge, \vee, \rightarrow, \neg, \exists, \forall$, and the binary predicate $=$. As already introduced, we have a constant individual assignment α, that is a partial function from Ind into $L_2[0, T]$. We also have a predicate assignment $\beta : \mathrm{Pred} \rightarrow \in \{0, 1\}^{k \times k}$. Now, the union $\gamma = \alpha \cup \beta$ is a comprehensive assignment of $PL^=$. The individual terms in the domain of α are individual constants, those not in the domain of α are individual variables. The syntactic operations of the language $PL^=$ and the set SF of sentential formulae as their recursive closure can be defined as follows, for arbitrary $a, b, z \in \mathrm{Ind}, F \in \mathrm{Pred}$, and $\phi, \psi \in SF$:

$$\sigma_= : (a, b) \mapsto a = b; \ \sigma_{\mathrm{pred}} : (a, F) \mapsto Fa; \quad \sigma_\neg : \phi \mapsto \neg\phi;$$
$$\sigma_\wedge : (\phi, \psi) \mapsto \phi \wedge \psi; \ \sigma_\vee : (\phi, \psi) \mapsto \phi \vee \psi; \ \sigma_\rightarrow : (\phi, \psi) \mapsto \phi \rightarrow \psi; \qquad (31.16)$$
$$\sigma_\exists : (z, \phi) \mapsto \exists z\phi; \quad \sigma_\forall : (z, \phi) \mapsto \forall z\phi.$$

The set of terms of $PL^=$ is the union of the sets of individual terms, predicates, and sentential formulae of the language. A sentential formula in SF is called a *sentence* with respect to some constant assignment γ if and only if, under assignment γ, all and only individual terms bound by a quantifier are variables. Any term of $PL^=$ is called γ-*grammatical* if and only if, under assignment γ, it is a predicate, an individual constant, or a sentence. Taking the idea at face value that eigenmodes can be treated like possible worlds (or more neutrally speaking: like models), the relation 'i neurally models ϕ to degree d by constant assignment γ', in symbols

$$i \models_\gamma^d \phi,$$

for any sentence ϕ and any real number $d \in [-1, +1]$, is then recursively given as follows:

Identity: Given any individual constants $a, b \in \mathrm{Ind} \cap \mathrm{dom}(\gamma)$, then $i \models_\gamma^d a = b$ iff $d = \Delta(\gamma(a), \gamma(b))$.

Predication: Given any individual constant $a \in \mathrm{Ind} \cap \mathrm{dom}(\gamma)$ and any predicate $F \in \mathrm{Pred}$, then $i \models_\gamma^d Fa$ iff $d = \max\{\Delta(\gamma(a), f_j) | \mathbf{f} = \gamma(F)\mathbf{v}_i c_i(t)\}$.

Conjunction: Provided that ϕ, ψ are sentences, then $i \models_\gamma^d \phi \wedge \psi$ iff $d = \min\{d', d'' | i \models_\gamma^{d'} \phi \text{ and } i \models_\gamma^{d''} \psi\}$.

Disjunction: Provided that ϕ, ψ are sentences, then $i \models_\gamma^d \phi \vee \psi$ iff $d = \max\{d', d'' \mid i \models_\gamma^{d'} \phi$ and $i \models_\gamma^{d''} \psi\}$.

Implication: Provided that ϕ, ψ are sentences, then $i \models_\gamma^d \phi \rightarrow \psi$ iff $d = \sup\{d' \mid \min\{d', d''\} \leq d'''$ where $i \models_\gamma^{d''} \phi$ and $i \models_\gamma^{d'''} \psi\}$.

Negation: Provided that ϕ is a sentence, then $i \models_\gamma^d \neg\phi$ iff (i) $d = 1$ and $i \models_\gamma^{-1} \phi$ or (ii) $d = -1$ and $i \models_\gamma^{d'} \phi$ where $d' < 1$.

Existential Quantifier: Given any individual variable $z \in \text{Ind} \setminus \text{dom}(\gamma)$ and any sentential formula $\phi \in SF$, then $i \models_\gamma^d \exists z\phi$ iff $d = \sup\{d' \mid i \models_{\gamma'}^{d'} \phi$ where $\gamma' = \gamma \cup \{\langle z, c\rangle\}$ and $c \in L_2[0, T]\}$.

Universal Quantifier: Given any individual variable $z \in \text{Ind} \setminus \text{dom}(\gamma)$ and any sentential formula $\phi \in SF$, then $i \models_\gamma^d \forall z\phi$ iff $d = \inf\{d' \mid i \models_{\gamma'}^{d'} \phi$ where $\gamma' = \gamma \cup \{\langle z, c\rangle\}$ and $c \in L_2[0, T]\}$.

Let me briefly comment on these definitions: Most of them should be familiar from previous sections. The degree d, however, is no longer treated as a function, but as a relatum in the relation $\models$.

The semantic evaluation of negation has previously only been defined for negated identity sentences. The generalized definition, here, is a straightforward application of the Gödel system.[7] An interesting feature of negation in the Gödel system is that its duplication digitalizes the values of d into $+1$ and -1.

The evaluation of implication, too, follows the Gödel system.[8] Calculi for our semantics have been developed in the literature. The calculi are in principle those of intuitionist logic (Gottwald, 2001; Werning, 2005c).

To evaluate existentially quantified formulae, the well-known method of cylindrification (Kreisel and Krivine, 1976) is adjusted to the many-valued case. The supremum (sup) takes over the role of existential quantification in the meta-language and can be regarded as the limit case of the maximum-function in an infinite domain. This is analogous to the common idea of regarding the existential quantifier as the limit case of disjunction over an infinity of domain elements. It should be noted that the value of an existentially quantified sentence of the form

$$(\exists z)(Fz)$$

measures whether the oscillators in the feature layer expressed by F oscillate.

For the evaluation of universally quantified formulae, the method of cylindrification is used and adjusted again. This time the infimum (inf) assumes the role of universal quantification in the metalanguage. It can be regarded as the limit case of the minimum for infinite domains in the same way as one might think of the universal quantifier as

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[7] In t-norm based many-valued logics a function $\mathbf{n} : [-1, +1] \rightarrow [-1, +1]$ is generally said to be a negation function if and only if $\mathbf{n}$ is non-increasing, $\mathbf{n}(-1) = 1$ and $\mathbf{n}(1) = -1$ (cf. Gottwald, 2001).

[8] The deeper rationale behind this definition is the adjointness condition, which relates the evaluation of implication to the t-norm (= min, by our choice). The adjointness condition relates the evaluation of implication, the function $\mathbf{i} : [-1, +1]^2 \rightarrow [-1, +1]$, to the t-norm $\mathbf{t}$ by the following bi-conditional (cf. Gottwald, 2001): $d' \leq \mathbf{i}(d'', d''') \Leftrightarrow \mathbf{t}(d', d'') \leq d'''$.
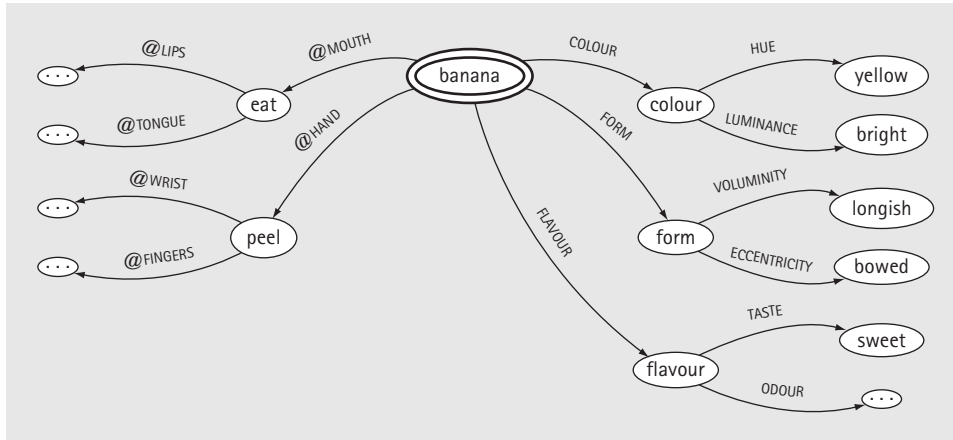
FIGURE 31.6 Hypothetical fragment of the frame for the representation of a banana. The substance representation to be decomposed is marked by a double circle as the referring node of the frame. The labelled arrows denote attributes, the nodes their values. Based on linguistic and neurobiological evidence (e.g. Pulvermüller, 2005), we assume that the representations of substances are linked to body-part related motor programmes. It could be theoretically shown how such a frame might translate into a complex pattern of synchronization where the peripheral attributes of the frame correspond to neuronal feature maps.

the limit case for infinite conjunction. To mention a concrete example, the value of a universally quantified implication of the form

$$(\forall z)(Fz \rightarrow F'z)$$

can be viewed as providing a measure for the overall synchronization between feature layers expressed by the predicates F and F'.

Werning (2003b) extends this semantics from an ontology of objects to an ontology of events. Werning (2003a) integrates relation like the in-relation. Using frame theory, Petersen and Werning (2007) and Werning (2008) show how our neuronal semantics deals with substance representations that decompose into attributive representations (see Fig. 31.6).

31.8 COMPOSITIONALITY AND EMULATIVE SEMANTICS

In this section I will finally prove that the principle of the compositionality of meaning is fulfilled for oscillatory networks. The work done so far leads us directly to the following theorem:

Theorem 1 (Compositionality of Meaning). *Let L be the set of terms of a PL$^=$-language, SF the set of sentential formulae and $\models$ the neuronal model relation. The function μ with domain L is a compositional meaning function of the language if μ, for every $t \in L$, is defined in the following way:*

$$\mu(t) = \begin{cases} \{\langle \gamma, \gamma(t) \rangle\} \text{ if } t \notin SF, \\ \{\langle \gamma, i \rangle | i \models^1_\gamma \phi\} \text{ if } t \in SF. \end{cases}$$

To simplify notation, we may stipulate for any γ-grammatical term t:

$$\mu_\gamma(t) = \begin{cases} \gamma(t) \text{ if } t \text{ is not a sentence,} \\ \{i | \langle \gamma, i \rangle \in \mu(t)\} \text{ if } t \text{ is a sentence.} \end{cases} \qquad (31.17)$$

Proof: To prove the theorem, one has to show that for any of the syntactic operations σ in (31.16), there is a semantic operation m_t that satisfies the equation:

$$\mu(\sigma(t_1, ..., t_n)) = m_\sigma(\mu(t_1), ..., \mu(t_n)). \qquad (31.18)$$

To do this for the first six operations, one simply reads the bi-conditionals in the definition of $\models$ as the prescriptions of functions:

$$m_= : (\mu(a), \mu(b)) \mapsto \{\langle \gamma, i \rangle | 1 = \Delta(\mu_\gamma(a), \mu_\gamma(b))\};$$

$$m_{\text{pred}} : (\mu(a), \mu(F)) \mapsto$$

$$\{\langle \gamma, i \rangle \ | 1 = \max\{\Delta(\mu_\gamma(a), f_j) | \mathbf{f} = \mu_\gamma(F)\mathbf{v}^i c_i(t)\}\};$$

$$m_\wedge : (\mu(\phi), \mu(\psi)) \mapsto \ \mu(\phi) \cap \mu(\psi);$$

etc.

To attain semantic counterpart operations for $\sigma_\exists$ and $\sigma_\forall$, we have to apply the method of cylindrification:

$$m_\exists : \mu(\phi(z)) \mapsto$$

$$\{\langle \gamma, i \rangle \ | \exists \gamma' : \text{dom}(\gamma') = \text{dom}(\gamma) \cup \{z\} \text{ and } \langle \gamma', i \rangle \in \mu(\phi(z))\};$$

$$m_\forall : \mu(\phi(z)) \mapsto$$

$$\{\langle \gamma, i \rangle \ | \forall \gamma' : \text{dom}(\gamma') = \text{dom}(\gamma) \cup \{z\} \Rightarrow \langle \gamma', i \rangle \in \mu(\phi(z))\}.$$

One easily verifies that the compositionality condition is satisfied. □

Theorem 1 proves that the dynamics of oscillatory networks provides a compositional semantics for a first-order language. The proof demonstrates that the method to define a semantics is completely analogous to what one usually does in standard model-theoretical semantics. It follows that the neuronal structure

$$\mathcal{N} = \langle\{\mu_\gamma[L_\gamma], \{m_=, m_{\mathrm{pred}}, m_\neg, m_\wedge, m_\vee, m_\rightarrow, m_\exists, m_\forall\}\rangle$$

is a compositional semantics for a language with the syntax

$$\langle L_\gamma, \{\sigma_=, \sigma_{pred}, \sigma_\neg, \sigma_\wedge, \sigma_\vee, \sigma_\rightarrow, \sigma_\exists, \sigma_\forall\}\rangle.$$

The meaning $\mu_\gamma(a)$ of an individual constant a can be regarded as an internal object representation. It is an oscillation that co-varies with an object in the stimulus. The stimulus object is to be identified with the denotation of the constant a. The content of the internal object representation expressed by the constant a is hence identical with the denotation of the constant. We should note that a is best conceived of as an indexical that tracks the object. Recall that the construction scheme of the network was chosen to implement the *Gestalt* principles for object perception: whatever yields an oscillation in the network must be regarded as an object of perception. Network simulations with ambiguous and illusionary stimuli support this view (Werning and Maye, 2006; Salari and Maye, 2008).

The meaning $\mu_\gamma(F)$ of a predicate F is identified with an internal predicative representation. It is the matrix that identifies a specific feature layer of a module. The activities of the layer, by construction, co-vary with instantiations of a certain property in the stimulus. We may denote this property by the predicate F. The content of the internal predicative representation expressed by the predicate F is identical with the denotation of the predicate.

The meaning of a sentence is a set of eigenmodes. We can regard it as an internal propositional representation. Since the meanings of constants and predicates are internal representations and co-vary with what they denote, the sets of eigenmodes can be mapped one–one to sets of models or possible worlds built from the denoted objects and properties. If one takes propositions to be sets of models or possible worlds, as is commonly done, and if one assumes that propositions are the denotations of sentences, we have a one–one mapping between the internal propositional representations of the network and the denotations of the sentences that express them. We may hence infer that the principle of content co-variation is fulfilled for the triples <constant term, internal object representation = oscillation, denoted object>, <predicate, internal object representation = feature layer, denoted property>, <sentence, internal propositional representation = set of eigenmodes, denoted proposition>.

The co-variation between the internal representations generated by the network and expressed by the terms of the language, on the one side, and the denotations of the expressions, on the other side, are one-to-one. Moreover, the semantic operations used to construct our neuronal semantics are also completely analogous to those used in the denotational semantics of standard model theory. It can thus be immediately shown that the neuronal structure $\mathcal{N}$, which provides a semantics of internal representations of our language, is strictly isomorphic to the denotational semantics one would get in the standard model-theoretical approach.[9] This isomorphism justifies the claim that

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[9] The proof is analogous to the one given in Werning (2005*c*).

the neuronal structure is an emulative semantics of a first-order language. It is non-symbolic because it is isomorphic to a denotational semantics as provided by standard model theory and thus violates the principle of semantic constituency. Each element of a denotational semantics for the perceptual expressions used in our language has a counterpart in the neuronal structure: its emulation.

31.9 CONCLUSION

Oscillatory networks show how a structure of the cortex can be analysed so that elements of this structure can be identified with internal representations. These cortical states can be regarded as the neuronal meanings of the expressions in a perceptual predicative language. As meanings they form a compositional semantics for such a language. As internal representations they co-vary with external content. The emulative semantics developed in this chapter is biologically realistic. It builds on neurobiological findings regarding cortical feature maps and object-relative synchronization. It also incorporates the Gestalt principles of perception.

Compared to connectionist alternatives (Smolensky, 1991/1995*a*; Shastri and Ajjana-gadde, 1993; Plate, 1995; van der Velde and de Kamps, 2006), the architecture proposed here as a model for large parts of the cortex is advantageous in that it not only implements a compositional semantics of meanings, but shows how internal representations can co-vary with external contents. As a consequence it becomes transparent how internal representation can have content and how they thereby mediate between expressions and their denotations.

Oscillatory networks and their biological correlates may be assigned a central role at the interface between language and mind, and between mind and world. This is due to the quasi-perceptual capabilities of oscillatory networks, which alternative connectionist models for semantic implementations lack. Linking oscillatory networks to mechanisms for the production of phonological sequences remains a challenge for future investigations.

The theory developed here amounts to a new mathematical description of the time-structure the cortex is believed to exhibit. Neuronal synchronization plays an essential role not only for binding, but, generally, for the generation of compositional representations in the brain.

According to our approach meanings are non-symbolic, but emulative. In contrast to symbolic theories there is no part–whole relation defined on meanings that reflects the part–whole relations of syntax. Instead, the denotational structure of linguistic expressions is emulated. A main aspect of Fodor's Language of Thought approach is to identify meanings with mental concepts and so 'duplicate' language. The principal idea of emulative semantics is that meanings 'duplicate' the world where duplication is taken to be neuronal emulation.

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