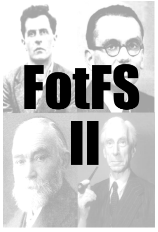

Benedikt **Löwe**, Wolfgang **Malzkorn**, Thoralf **Räsch** (*eds.*)
Foundations of the Formal Sciences II
Applications of Mathematical Logic in Philosophy and Linguistics
Bonn, November 10-13, 2000, pp. 255–272.

Synchrony and Composition: Toward a Cognitive Architecture Between Classicism and Connectionism

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Abstract. Using the tools of universal algebra, it is shown that oscillatory networks realize systematic cognitive representations. It is argued (i) that an algebra of propositions and concepts for objects and properties is isomorphic to an algebra of brain states, neuronal oscillations and sets of oscillations related to clusters of neurons, (ii) that the isomorphism, in a strong sense, preserves the constituent relations of the conceptual algebra, and (iii) that the isomorphism transfers semantic compositionality. Oscillatory networks are neurobiologically plausible. They combine the virtues and avoid the vices of classical and connectionist architectures.

Received: April 1st, 2001;
In revised version: July 24th, 2001;
Accepted by the editors: August 17th, 2001.
2000 *Mathematics Subject Classification.* **92B20** 08A70 91F20 91E10 68T99.

[⋆] Research for this paper was sponsored by the National German Scholarship Foundation. It was enabled by a one-year research scholarship at Rutgers University and the Rutgers Center of Cognitive Science. I owe many of the presented insights to discussions with Andreas Engel, Wolf Singer, Jerry Fodor, Ernie LePore, Brian McLaughlin, Bruce Tesar, Thomas Metzinger, and Gerhard Schurz. I have benefitted from comments by a number of colleagues on various occasions where parts or earlier stages of this material were presented. I am grateful, in particular, to participants at the Berlin Colloquium *Philosophy Meets Cognitive Science*, FotFS II, CogSci2001, and ESPP2001. I would, also, like to thank an anonymous referee for very helpful remarks.

1 Introduction

Minds have the capacity to compose contents. Otherwise, they would not show a systematic correlation between representational capacities: If a mind is capable of certain intentional states in a certain intentional mode, it most probably is also capable of other intentional states with related contents in the same mode. The capacity to see something as a red square in a green circle, *e.g.*, is statistically highly correlated with the capacity to see something as a red circle in a green square. The capacity to understand the English sentence “John loves Mary” is correlated with the capacity to understand “Mary loves John”. To explain this correlation, compositional operations are postulated (Throughout the text operations are conceived of as functions). They enable the system to build complex representations from primitive ones so that the semantic value of the complex representation is determined by its structure and by the semantic values of its components. Several cognitive theories have been developed to meet the requirement of compositionality. The proposed theories, though, suffer from severe deficits.

Fodor and Pylyshyn [FodPyl88] for one take recourse to a language of thought, which they link to the claim that the brain can be modelled by a Turing-style computer. A subject’s having an intentional state, they believe, consists in the subject’s bearing a computational relation to a mental sentence; it is a relation analogous to the relation a Turing machine’s control head bears to the tape. A subject’s belief that there is a red square in a green circle, thus, is conceived of as a computational relation between the subject and the mental sentence: *There is a red square in a green circle*. Likewise, when a subject understands the utterance“John loves Mary”, this utterance reliably causes the subject to bear a computational relation to the mental sentence: *John loves Mary*. According to this paradigm, the mind composes complex representations from primitive ones just the way a computer combines phrases from words: by concatenation. The mental sentence –or thought– *John loves Mary* is hence nothing but a concatenation of the mental words – or concepts – *Mary, John,* and *loves*. Given a certain syntactic structure, the semantic properties of the thought are completely determined by the semantic properties of the concepts.

The trouble with classical computer models is well known and reaches from the frame problem, the problem of graceful degradation, and the problem of learning from examples (*cf.* [Hor$_0$Tie$_1$96]) to problems that arise from the content sensitivity of logical reasoning (*cf.* [GigHug$_0$92]). To avoid the pitfalls of classicism, connectionist models have been developed. In Smolensky's integrated connectionist/symbolic architecture [Smo91] the terms and the syntax of a language are mapped homomorphically onto an algebra of vectors and tensor operations.[1] Each primitive term of the language is assigned to a vector. Every vector renders a certain distribution of activity within the connectionist network. The syntactic operations of the language have tensor operations as counterparts. As far as syntax is concerned, languages with rich combinatorial potential can, indeed, be implemented by a connectionist network.

The kind of combination that is necessary for systematicity, however, focuses not only on syntactic, but also on semantic features. The capacity to think that a child with a red coat is distracted by an old herring is not correlated with the capacity to think that a child with an old coat is distracted by a red herring. The thoughts ought to be correlated, though, if the fact that one is a syntactic re-combination of the other was sufficient for systematic correlation. Notice that both thoughts are syntactically combined from exactly the same primitives by exactly the same operations. One may, however, well have the capacity to think of red coats and old herrings even though one lacks the capacity to think of red herrings. The two thoughts fail to be correlated because *red herring* is idiomatic and –as a consequence– semantic compositionality is violated.

Formally speaking, a language is semantically compositional if and only if its semantics is a homomorphic image of its syntax (*cf.* [PartMeWal$_0$90]): Let $\mathcal{S} = \langle S_1, ..., S_n; s_1, ..., s_r \rangle$ be the syntax algebra of the language with the syntactic categories $S_1, ..., S_n$ (*e.g.*, sets of adjectives or nouns) and with the syntactic operations $s_1, ..., s_r$ (*e.g.*, adjective-noun combination); and let $\mathcal{M} = \langle M_1, ..., M_n; m_1, ..., m_r \rangle$ be the semantic algebra of the language with the semantic categories and operations. In the case of a homomorphism we have a family of functions $\langle v_i : S_i \to M_i | i = 1, ..., n \rangle$ that allows us to define the function v

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[1] I take Smolensky's approach only as a representative for a variety of models that pursue a similar strategy. For a survey of related models see [Wer01].

of semantic evaluation in the following way:

$$v : S_1 \cup ... \cup S_n \cup \{s_1, ..., s_r\} \to M_1 \cup ... \cup M_n \cup \{m_1, ..., m_r\} \quad (1.1)$$
$$\text{such that } v(\alpha) = v_i(\alpha) \text{ if } \alpha \in S_i \text{ for every } i = 1, ..., n$$
$$\text{and } v(s_j) = m_j \text{ for every } j = 1, ..., r.$$

Using the definition of homomorphism, we can now say that a language is compositional if and only if the semantic evaluation function distributes over the syntactic structure of any of the language's formulas:

$$v(s_j(\alpha_1, ..., \alpha_{k_j})) = v(s_j)(v(\alpha_1), ..., v(\alpha_{k_j})). \quad (1.2)$$

This equation nicely interprets the informal definition of compositionality according to which the semantic value of a complex formula is determined by its syntactic structure and the semantic values of its syntactic components. Syntactic operations that violate (1.2) generate idioms. That some idioms, at least, undermine semantic compositionality can be demonstrated with regard to the example *red herring*. Provided, firstly, that the semantic values of *red herring* and *not-not-red herring* differ – the value of the former relates to a maneuver of drawing attention away from the main issue, whereas that of the latter relates to some redly colored fish–, provided, secondly, that the semantic values of *red* and *not-not-red* are the same, and provided, thirdly, that *red herring* and *not-not-red herring* are outcomes of the same syntactic operation –with *red* and *herring* as arguments in the one and *not-not-red* and *herring* in the other case–, this syntactic operation, then, has no semantic function as counterpart. Recall that no function outputs different values if it takes the same items as arguments. With these three rather plausible provisions, the idiomatic character of *red herring* constitutes a violation of semantic compositionality as defined above.[2] As we have seen, idioms undermine the

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[2] I do not intend to make any substantial statements about idioms, here. In an objection to the received view, which is reflected in [NunSagWas94] and according to which some idioms violate semantic compositionality, Westerståhl [Wes∞] argues that idioms can always be embedded in compositional languages. He proposes three ways of doing so: (i) extend the set of atomic expressions by a holophrastic reading of the idiom, (ii) extend the list of syntactic operations so that the literal and the idiomatic reading of the idiom turn out to be outcomes of different syntactic operations, or (iii) take the components of the idiom as homonyms of their occurrences in its literal reading and add them to the set of atomic expressions. None of the three options afflict our argumentation, though, because in each case *a child with an old coat is distracted by a red herring* would no longer be a syntactic re-combination of *a child with a*

systematic correlation of two thoughts even when one thought is nothing but a syntactic re-combination of the other. We may, hence, infer that semantic compositionality is necessary for systematicity –its violation would allow for idioms– and that syntactic combination is not sufficient. Smolensky's strategy to implement the syntax of a language onto a connectionist network does not suffice to establish that the network itself subserves systematic representational capacities.

2 Constituency

A further argument provides us with a deeper insight into what's wrong with connectionist approaches toward representationalism. Most semantic theories explain the semantic properties of internal representations either in terms of co-variance, in terms of inferential relations, in terms of associations, or by a combination of the three. Some, *e.g.*, hold that a certain internal state is a representation of redness because the state co-varies with nearby instances of redness. This co-variance relation is, of course, backed by the intrinsic and extrinsic causal properties of the *redness* representation. Others hold that some representations *–e.g.*, *bachelor–* characteristically are such that the subject is disposed to infer other representations *–e.g.*, *unmarried–* from it. Those dispositions, again, are grounded in the causal properties of the representations in question. One may, thirdly, hold that the semantic value of a representation like *cow* is determined by the fact that it is associated with other representations, *e.g.*, *milk*, *leather*, *mammal*, *grass*, etc. The mechanism of association, too, supervenes on the causal properties of the representation in question. All of these theories have one principle in common: An internal representation has its semantic value because it has a certain causal role within the system (and –perhaps– the rest of the world).

The question of how the semantic value of an internal representation is determined, and perforce, how it is determined by the semantic values of its syntactic components, hence, leads to the question of how the causal properties of an internal representation are determined—and perforce how they are determined by the causal properties of the syntactic components. From chemistry and other sciences we know that

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red coat is distracted by an old herring. This, however, would simply negate the assumption that it is. The assumption has been made for the sake of the argument with the intention to show that syntactic re-combination is not sufficient for systematicity.

atoms determine the causal properties of molecules *because* atoms are *constituents* of molecules. A state X is commonly regarded to be a constituent of a state Y if and only if it is necessarily and generally true that, if Y occurs at a certain region of space at a certain time, then X occurs at the same region at the same time. Independently from sciences, one can even make it a hard metaphysical point: If the causal properties of a state B are determined by the causal properties of the states $A_1, ..., A_n$ and their relations to each other, then $A_1, ..., A_n$ are constituents of B.[3] We may conclude that the semantic values of the syntactic components of an internal representation determine the semantic value of the internal representation just in case the syntactic components are constituents of the internal representation. Two remarks should be added: First, syntactic components aren't constituents *per se*. The article "le" is a syntactic component, but not a constituent of the French "l'homme". Second, the requirement that syntactic components of internal representations be constituents of the latter does not follow from the constraint of compositionality alone. There may well be compositional languages (in the sense defined above) for which syntactic components aren't constituents. However, the requirement is justified by the constraint of compositionality together with the premise that internal representations owe their semantic values to the causal role they play for the representational system. This premise highlights a particularity of *internal* representation and does not generalize to other representational media like natural languages. The words and phrases of English, *e.g.*, owe their semantic val-

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[3] There is an independent argument for this principle, which however requires Kim's [Kim89] principle of explanatory exclusion. The principle roughly says that no two independent phenomena each (completely) determine one and the same phenomenon. Given the truism that the causal properties of a whole B are determined by the causal properties of an exhaustive sample $C_1, ..., C_m$ of constituents of B (plus structure), it follows that the causal properties of the states $A_1, ..., A_n$ (plus structure) determine the causal properties of B only if $A_1, ..., A_n$ are not independent from $C_1, ..., C_m$. Since there is a limited repertoire of relevant metaphysical dependency relations, viz. identity, reduction, supervenience and constituency, one may conclude that each A_i is either (i) identical with, (ii) reducible to, (iii) supervenient on, (iv) a constituents of, (v) or composed of one or more of the C_j. In all five cases every A_i would be a constituents of B. In the first case, this is trivial. In the second and the third case, if A_i reduces to, or is supervenient on, one or more of the C_j, A_i necessarily co-occurs with the C_j in question. Since the latter, as constituents of B, necessarily occur whenever and wherever B does, also A_i necessarily occurs whenever and wherever B does and is, thus, a constituent of B. In the fourth case, it follows because the relation of constituency is transitive. The fifth case holds because every composition of constituents of a whole is itself a constituent of the whole.

ues mainly to the interpretation of English speakers. There may well be a language whose tokens have the same causal properties (sound, loudness, etc.) as those of English, but differ with respect to their semantic values. For internal representation, in contrast, causal properties are decisive with regard to semantics because internal representations represent autonomously, *i.e.*, without being interpreted by any other system.[4]

Connectionist attempts to render systematicity, we may now diagnose, fail because the mapping between the language's syntax and the network does not preserve the constituent relations within the language. Thus, even if the language to be syntactically implemented is itself semantically compositional and even if every syntactic component in the language is a constituent (as is the case for many formal languages), the mapping does not transfer semantic compositionality.[5] In Smolensky's architecture, the network counterparts of, say, *brown* and *cow* aren't constituents of the network counterpart of *brown cow*. Although the syntactic operation that maps (*brown*, *cow*) onto *brown cow* may satisfy the principle of semantic compositionality, the network operation that maps $(h(brown), h(cow))$ onto *h(brown cow)* –with h being the homomorphism between the language and the network– may well violate semantic compositionality. If $h(brown)$ and $h(cow)$ aren't constituents of $h(brown\ cow)$ you, *e.g.*, cannot say: $h(brown\ cow)$ co-varies with brown cows *because* $h(brown)$ co-varies with brown things and $h(cow)$ co-varies with cows. If the semantic values of internal representations are to be determined by the semantic values of their syntactic components (plus structure) and if semantic evaluation is done by co-variation, you ought to be able to say this. If the constituent relations, on the other hand, had indeed been preserved, you could have said this.[6] For similar reason, you will be deprived of the possibility to explain the inferential and the associative properties of the complex representation on the basis of the inferential and the associative properties of the primitive representations if constituency structures are not preserved and causal properties are, therefore, not determined bottom-up from the primitives to the complex. Thus, if semantic evaluation corresponds to inferential role or asso-

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[4] This point is made in a more elaborate way by Dretske [Dre88a].

[5] This holds even if the mapping is an isomorphism rather than a homomorphism.

[6] Fodor and McLaughlin [FodMcL90,Fod97] also see a connection between the ideas of compositionality, co-variation and constituency.

ciative nets, the principle of compositionality will again not be warranted by Smolensky's architecture.

3 Synchrony

Constituency is a synchronic relation, while causal connectedness is a diachronic relation. Whole and part co-exist in time, whereas causes and effects succeed in time. The reference to causal connections and the flow of activation within the network will, therefore, not suffice to establish constituent relations. What we, in addition, need is an adequate synchronic relation. Oscillatory networks provide a framework to define such a relation: the relation of synchrony between oscillations.

An elementary oscillator is realized by coupling an excitatory unit with an inhibitory unit using delay connections. An additional unit allows for external input (see Figure 1a). Within the network, oscillatory elements are coupled by either short-range synchronizing connections or long-range desynchronizing connections (see Figure 1b). A multitude of oscillators can be arranged in feature modules (*e.g.*, the color module), employing appropriate patterns of connectivity. Given a certain selectivity of the input unit, each oscillator is designed to indicate a certain property (*e.g.*, redness) within the feature domain. Oscillators for like properties are connected synchronizingly, those for unlike properties are connected desynchronizingly. The behavior of oscillatory networks has been studied in detail elsewhere (*cf.* [$\mathrm{Sch}_2\mathrm{Kön}_1$94]).[7] Stimulated oscillatory networks, characteristically, show object-specific patterns of synchronized and desynchronized oscillators within and across feature modules. 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 networks. The oscillation pertains only to oscillators that represent the properties of the object in question (see Figure 2).

A great number of neurobiological studies have by now corroborated the view that cortical neurons are rather plausibly modelled by oscillatory networks (for a survey *cf.* [$\mathrm{Sin}_1\mathrm{Gra}_1$95,Wer01]). Together with the computer simulations of [$\mathrm{Sch}_2\mathrm{Kön}_1$94], these studies support two hypotheses:

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[7] Oscillatory networks are dynamical systems in the sense that they are described by systems of differential equations that involve time-dependent functions (*cf.* [vGe98]).

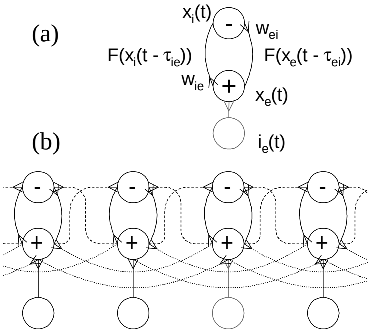

Fig. 1. (a) Elementary oscillator. t, tir unit activity; $F(x)$ sigmoidal output w, coupling weight; τ, delay time; i ternal input. Subscripts: e, excitatory inhibitory unit. (b) Oscillatory eleme pled by short-range synchronizing cor (dashed) and long-range desynchroniz nections (dotted).

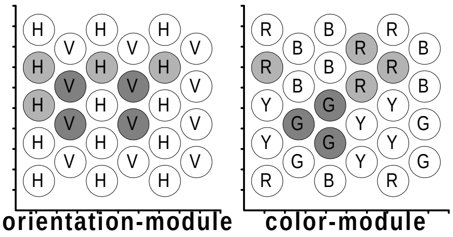

Fig. 2. Scheme of a typical response aroused in the appropriate receptive field by a green vertical stimulus object and a red horizontal stimulus object. Circles with letters signify oscillators/neurons with the property they indicate (H, V: horizontal, vertical; R, G, B, Y: red, green, blue, yellow). Like shadings signify synchronous activity.

Hypothesis 1 (Indicativity). There are clusters of neurons whose function it is to show activity only when an object in the receptive field instantiates a certain property. These clusters are called π-clusters with π being the property indicated.

Hypothesis 2 (Synchrony). Neurons of different π-clusters have the function to show the same oscillation (*i.e.*, to be activated synchronously) only if the properties indicated by each π-cluster are instantiated by the same object in the receptive field.

In other words, the sameness of oscillations indicates the sameness of objects, and an oscillation's pertaining to a π-cluster indicates that the object indicated by the oscillation has the property π.

4 Algebra

Oscillatory networks that implement the two hypotheses can be given an abstract algebraic description. To define such an algebra, we have to introduce a number of notions. First, we take brain states to be sets of time slices of brains. Each time slice covers a temporal interval. An individual brain is in a certain brain state during the interval $I = [-T/2, +T/2]$ just in case its time slice belongs to the appropriate set of time slices of brains. If Br is the set of all possible time-slices of brains covering the interval I, then the power set $\wp(Br)$ is the set of all possible brain states during I. Second, let Osc be the set of all oscillations during I. An oscillation $a(t)$ is the (quasi-periodic) spiking activity of a neuron as a function of time during a temporal interval. Mathematically speaking, these oscillations are vectors in the Hilbert space $L_2[-T/2, +T/2]$ of in the interval square-integrable functions. This space has the countable basis

$$\left\{\frac{1}{\sqrt{T}}\exp(\frac{ni2\pi t}{T}) \mid n \in \mathbb{Z}\right\} \tag{4.1}$$

and the inner product

$$\langle a(t)|b(t)\rangle = \int_{-T/2}^{+T/2} \overline{a(t)}b(t)dt. \tag{4.2}$$

The degree of synchrony between two oscillations lies between 0 and 1 and is defined as $\Delta(a,b) = \langle a|b\rangle/\sqrt{\langle a|a\rangle\langle b|b\rangle}$.[8] Third, a set of oscillations can be assigned to each π-cluster of neurons. Such a set –let's call it π-set– contains all oscillations that the neurons of the π-cluster show during I. Let Cl be the set of all π-sets. We can now define the neuronal algebra $\mathcal{N}$, which comprises three carrier sets and four operations:

$$\mathcal{N} = \big\langle \mathrm{Osc}, \mathrm{Cl}, \wp(Br); =^N, \neq^N, \in^N, \wedge^N \big\rangle. \tag{4.3}$$

By convention, we use "a" and "b" as symbols for elements of Osc, capital letters for elements of Cl, and "p" and "q" for elements of $\wp(Br)$. It will be clear from context whether we use the symbols as variables or constants and whether they are interpreted in $\mathcal{N}$. Quotation marks are omitted where appropriate. Each of the four operations has brain states as values. Let us first define the operation of *synchrony*:

$$\begin{gathered} =^N\!: \text{Osc} \times \text{Osc} \to \wp(Br) \text{ such that} \\ (a,b) \mapsto \{\beta \in Br \mid \beta \vDash a = b\} =_{\mathrm{df}} [a=b]^N. \end{gathered} \tag{4.4}$$

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[8] The degree of synchrony, so defined, corresponds to the cosine of the angle between the vectors a and b. Alternative measures for synchrony (respectively temporal coherence) are available, in particular for discrete functions of spiking activity.

This operation maps two oscillations a and b onto a brain state $[a = b]^N$, which is the set of those temporal brain slices which make it true that a equals b. Since the equality of oscillations is a fuzzy notion and depends on the degree of synchrony between them, it is useful to furthermore define a closeness function $c : \wp(Br) \to [0,1]$. It tells us how close a concrete brain, which for reasons of simplicity is held constant, comes to an ideal brain state. We identify the closeness of a concrete brain to the ideal state, in which the oscillations a and b are absolutely synchronous, with the degree of synchrony between the oscillations a and b as occurring in the concrete brain: $c([a = b]^N) = \Delta(a, b)$.

The operation of *asynchrony* is defined analogously:

$$\begin{gathered}\neq^N\!: \text{Osc} \times \text{Osc} \to \wp(Br) \text{ such that} \\ (a,b) \mapsto \{\beta \in Br \mid \beta \vDash a \neq b\} =_{\text{df}} [a \neq b]^N.\end{gathered} \tag{4.5}$$

The corresponding closeness value is set to: $c([a \neq b])^N = 1 - \Delta(a, b)$.

If neurons of a certain π-cluster show a certain oscillation, we can say that the oscillation pertains to the π-cluster. Alternatively, we may say that the oscillation is element of the π-set of oscillations that relates to the π-cluster of neurons. To refer to this state, we define the operation of *pertaining*:

$$\begin{gathered}\in^N\!: \text{Osc} \times \text{Cl} \to \wp(Br) \text{ such that} \\ (a,F) \mapsto \{\beta \in Br \mid \beta \vDash a \in F\} =_{\text{df}} [a \in F]^N.\end{gathered} \tag{4.6}$$

How close a concrete brain comes to the state $[a \in F]^N$ depends on the highest degree of synchrony between the oscillation a and any oscillation among the cluster of neurons that contribute to the π-set F: $c([a \in F]^N) = max\{\Delta(a,x) \mid x \in F\}$. A further, trivially defined operation is the *co-occurrence* of two states:

$$\begin{gathered}\wedge^N : \wp(Br) \times \wp(Br) \to \wp(Br) \text{ such that} \\ (p,q) \mapsto p \cap q =_{\text{df}} [p \wedge q]^N.\end{gathered} \tag{4.7}$$

In fuzzy logic it is quite common to identify the value of a conjunction as the minimum of the values of either conjunct: $c([p \wedge q]^N) = min\{c(p)$, c(q)$\}$. The four operations allow us to give an algebraic interpretation of the scheme shown in Figure 2. Assuming that the dark-shaded neurons show the oscillation a and the light-shaded neurons b, Figure 2 expresses the following brain state (The associativity of co-occurrence derives from the associativity of set intersection):

$$[a \in V \wedge a \in G \wedge b \in H \wedge b \in R \wedge a \neq b]^N. \tag{4.8}$$

The closeness value of this state equals 1 only if a and b are orthogonal.

5 Language

We will now define an algebra $\mathcal{L}$ of indexical concepts, property concepts, and propositions. It will turn our to be isomorphic to $\mathcal{N}$. Since it is controversial whether concepts and propositions are semantic or (in the sense of Fodor's [Fod75] language of thought) syntactic entities, I will remain neutral on this issue, for now, and leave the philosophical interpretation of $\mathcal{L}$ for discussion at the end of this paper. I take propositions to be sets of possible worlds. Provided that Wr be the set of all possible worlds, the power set $\wp(Wr)$ is the set of all propositions.[9] Let Ind be a set of indexical concepts like *this* and *that*, which potentially refer to objects. Let Pr be a set of property concepts like *redness* and *verticality* where properties are conceived of merely as sets of objects. Like $\mathcal{N}$, $\mathcal{L}$ comprises three carrier sets and four operations:

$$\mathcal{L} = \left\langle \mathrm{Ind}, \mathrm{Pr}, \wp(Wr); =^L, \neq^L, \in^L, \wedge^L \right\rangle. \tag{5.1}$$

In the context of $\mathcal{L}$, we use the linguistic items "a" and "b" to express indexical concepts, capital letters to express property concepts, and "p" and "q" to express propositions. Alternatively, one may well use English words and phrases to express entities of $\mathcal{L}$. Notice that the complex concept that is expressed by the sentence "$a = b$" does not mean that the concepts a and b are identical. It rather expresses a proposition about the

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[9] The assumption that the class of possible worlds is a set may impose some restrictions on the universe. It is debatable, furthermore, whether it makes sense to say that every set of possible worlds is a proposition. An analogous objection may apply to the view that identifies every set of time slices of brains with a brain state. Notice, however, that only the sets of possible worlds (and their intersections) –and the sets of time slices of brains (and their intersections), respectively– which are in the ranges of the first three algebraic operations matter for our considerations, anyway. For an appropriate restriction of the algebras see p. 267.

identity of the objects referred to by the concepts a and b.[10] The first operation of $\mathfrak{L}$ is defined as follows:

$$\text{Sameness: } =^L\text{: Ind} \times \text{Ind} \to \wp(Wr) \text{ such that} \tag{5.2}$$
$$(a, b) \mapsto \{\omega \in Wr \mid \omega \vDash a = b\} =_{\text{df}} [a = b]^L.$$

The sameness operation maps two concepts a and b onto a proposition. The latter is the set of those possible worlds that make the complex concept which is expressed by the sentence “$a = b$” true. The remaining operations are defined analogously:

$$\text{Difference: } \neq^L\text{: Ind} \times \text{Ind} \to \wp(Wr) \text{ such that} \tag{5.3}$$
$$(a, b) \mapsto \{\omega \in Wr \mid \omega \vDash a \neq b\} =_{\text{df}} [a \neq b]^L.$$
$$\text{Copula: } \in^L\text{: Ind} \times \text{Pr} \to \wp(Wr) \text{ such that} \tag{5.4}$$
$$(a, F) \mapsto \{\omega \in Wr \mid \omega \vDash a \in F\} =_{\text{df}} [a \in F]^L.$$
$$\text{Conjunction: } \wedge^L : \wp(Wr) \times \wp(Wr) \to \wp(Wr) \text{ such that} \tag{5.5}$$
$$(p, q) \mapsto p \cap q =_{\text{df}} [p \wedge q]^L.$$

The operations enable us to denote the proposition which the English sentence “This is a green vertical and that is a red horizontal object” expresses (We assume that “this” and “that” express the concepts a and b, and “green”, “red”, “vertical”, “horizontal” express the concepts G, R, V, and H; the associativity of the conjunction $\wedge^L$ derives from the associativity of set intersection.):[11]

$$[a \in V \wedge a \in G \wedge b \in H \wedge b \in R \wedge a \neq b]^L. \tag{5.6}$$

6 Isomorphism

To establish the isomorphism, we, first, reduce the third carrier set of each algebra to that one of its subsets that is the closure of the united

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[10] A crucial difference between the notions of expressing and referring should not be overlooked here. In the English sentence “this is the same as that”, “this” and “that” do not *refer* to concepts, but to objects. They, nevertheless, *express* the concepts *this* and *that*.

[11] For reasons of simplicity, we have assumed, furthermore, that natural languages obey a set-theoretic rather than a predicative logic. Thus, “this is red” is analyzed as “this”$\frown$“$\in$”$\frown$“red” rather than, in a predicative way, as “red(this)”. Alternatively, one may change definition 5.4 by substituting “$F(a)$” for “$a \in F$”.

ranges of the first three operations under the forth operation (The so reduced algebras are marked by superscript "R"). Let the so attained reduction of $\wp(Br)$ be the set $Stat$, which, hence, comprises only brain states constructible in the neuronal algebra; and let the reduction of $\wp(Wr)$ be the set $Prop$, which, thus, is restricted to propositions constructible in the conceptual algebra. Secondly, we will treat both algebras modulo equivalence: $\mathcal{N}^R_{/\equiv} = \left\langle \mathrm{Osc}, \mathrm{Cl}, [Stat]_\equiv; =^N, \neq^N, \in^N, \wedge^N \right\rangle$ and $\mathcal{L}^R_{/\equiv} = \left\langle \mathrm{Ind}, \mathrm{Pr}, [Prop]_\equiv; =^L, \neq^L, \in^L, \wedge^L \right\rangle$. $\mathcal{N}^R_{/\equiv}$ is isomorphic to $\mathcal{L}^R_{/\equiv}$, provided that (i) there are as many oscillations in $\mathcal{N}$ as there are indexical concepts in $\mathcal{L}$ (*i.e.*, $|\mathrm{Osc}| = |\mathrm{Ind}|$) and (ii) each π-cluster, respectively, each related set of oscillations in $\mathcal{N}$ is assigned to exactly one property concept of $\mathcal{L}$ (*i.e.*,$|\mathrm{Cl}| = |\mathrm{Pr}|$).

In previous sections we argued that an architecture may not be compositional even if it is syntactically homomorphic (or even isomorphic) to a compositional language. To preserve semantic compositionality, the isomorphism between $\mathcal{L}^R_{/\equiv}$ and $\mathcal{N}^R_{/\equiv}$ must, in addition, preserve constituent structure: If a primitive concept is a constituent of a complex concept, the isomorphic counterpart of the primitive concept must be a constituent of the isomorphic counterpart of the complex concept. This is warranted: The oscillation a is a constituent of the brain states $[a = b]^N$, $[a \neq b]^N$ and $[a \in F]^N$ because it occurs whenever and wherever the brain states occur.[12] Likewise, the cluster of neurons which contribute to the π-set F are constituents of the state $[a \in F]^N$. The fact that primitive concepts are constituents of complex concepts is, thus, reflected in the neuronal algebra. Figure 2 illustrates that the isomorphism preserves constituent relations for all operations: The complex state shown can only occur if, indeed, certain bursts of activity and certain clusters of neurons occur. We may infer that oscillatory networks are not only isomorphic to a compositional language, but may subserve a way of representation that is semantically compositional in its own right (For further interpretation see the concluding section).

Having once shown the isomorphism and the congruence with respect to constituent structure, we can extend the rather simple algebras $\mathcal{N}$ and $\mathcal{L}$ in parallel, *i.e.*, in a manner that perpetuates the isomorphism and the congruence of constituent structure. This way, predictions about

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[12] Notice that "=" and " $\neq$ " denote relations and that relations obtain just in case the relata are tokened: $a = b \Vdash (\exists x)(x = b)$ and $a \neq b \Vdash (\exists x)(x \neq b)$.

the realization of structurally more sophisticated representations by oscillatory networks are generated. I will sketch an example that has to do with the representation of relations like *in*. On the conceptual level, this, in addition to $\mathcal{L}$, requires concepts for *pairs*, for *relations*, and a *higher-order copula*. If we take concepts for relations as primitive and as elements of the set Rel, we can define the remaining operations. We adopt Kuratowski's [KurMos$_2$76] convention, according to which pairs are asymmetric sets of second order:

$$\text{Pairing: } \langle\cdot\cdot\rangle^L : \mathrm{Ind} \times \mathrm{Ind} \to \wp(\wp(\mathrm{Ind})) \text{ such that} \qquad (6.1)$$
$$(a, b) \mapsto \{\{a, b\}, \{b\}\} =_{\text{df}} \langle a, b\rangle.$$

If Pair is the range of the pairing operation and if relations are sets of pairs with $\mathrm{Rel} \subset \wp(\mathrm{Pair})$, the second-order copula comes to:

$$\text{Second Copula: } \in_2^L\text{: } \mathrm{Pair} \times \mathrm{Rel} \to \wp(Wr) \text{ such that} \qquad (6.2)$$
$$(x, R) \mapsto \{\omega \in Wr \mid \omega \vDash x \in R\} =_{\text{df}} [x \in_2 R]^L.$$

The additional operations allow us to denote the proposition expressed by the sentence "This green object is in that red object":

$$[a \in G \wedge b \in R \wedge \langle a, b\rangle \in_2 In]^L. \qquad (6.3)$$

To capture relational representations by oscillatory networks, we simply have to proceed in a parallel way with extending $\mathcal{N}$. We define a pairing of oscillations. Let the range of this operation be the set OPair. We, furthermore, postulate relational modules as elements in the set RelM so that $\mathrm{RelM} \subset \wp(\mathrm{OPair})$:

$$\langle\cdot\cdot\rangle^N : \mathrm{Osc} \times \mathrm{Osc} \to \wp(\wp(\mathrm{Osc})) \text{ such that} \qquad (6.4)$$
$$(a, b) \mapsto \{\{a, b\}, \{b\}\} =_{\text{df}} \langle a, b\rangle;$$
$$\in_2^N\text{: } \mathrm{OPair} \times \mathrm{RelM} \to \wp(Br) \text{ such that} \qquad (6.5)$$
$$(x, R) \mapsto \{\beta \in Br \mid \beta \vDash x \in R\} =_{\text{df}} [x \in_2 R]^N.$$

This extension predicts that, in order to represent relations, some neurons fire with a set of two oscillations, rather than with a single oscillation. This kind of duplex activity can be achieved either by superposition or by modulation of two oscillations. Figure 3 provides an illustration.[13]

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[13] The topographical arrangement in the in-module does not have any representational function. The surrounding neurons with simplex activity may, however, help drive the embedded neurons to show duplex activity (*cf.* [May01]).

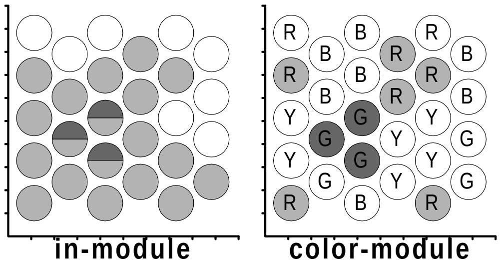

Fig. 3. Predicted neuronal representation of relations. The state $[a \in G \wedge b \in R \wedge \langle a, b\rangle \in_2 In]^N$ is shown. The oscillation a of the G-neurons (dark-shading) occurs in the in-module only as superposed with, or modulated by, the oscillation b of the R-neurons (light-shading), thus forming the duplex oscillation $\{a, b\}$ (hybrid shading). Since b also occurs as simplex on the in-module, the situation on the in-module is rendered by $[\{\{a, b\}, \{b\}\} \in_2 In]^N$. This is equivalent to $[\langle a, b\rangle \in_2 In]^N$.

7 Conclusion

Any comprehensive philosophical interpretation of our results would, by far, go beyond the scope of this paper. Let me, still, comment briefly on the nature of $\mathcal{L}$ and $\mathcal{N}$. Are they syntactic or semantic algebras? First of all, $\mathcal{L}$ has all the properties that are typical for the semantics of a language whose syntax allows us to build simple set-theoretic (or predicative) sentences.[14] It can easily be shown that $\mathcal{L}$ is the homomorphic image of such a syntax. Semantic compositionality is, hence, warranted. Since $\mathcal{N}$ and $\mathcal{L}$ are isomorphic (in their reduced forms and modulo equivalence), this homomorphism transfers to $\mathcal{N}$.

We may now interpret $\mathcal{L}$ in an externalistic way, where propositions are treated as mind-independent entities. Since propositions have been defined as sets of possible worlds, this interpretation corresponds to a realistic attitude toward possible worlds in the sense of Lewis [Lew86]. Since the brain states in $\mathcal{N}$ would be the isomorphic counterparts of these externalistic propositions, we might say that the brain produces simulations of them. The closeness value $c([p]^N)$ could be interpreted as a degree of resemblance between the subject's brain and the proposition $[p]^L$.

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[14] For the adaption to predicative languages see footnote 11. The simple set-theoretic language I have in mind is limited to syntactic operations regarding the connectives "$=$", "$\neq$", "$\in$" and "$\wedge$", and, with respect to the extended algebra, the symbols for pairing.

Alternatively, we could interpret $\mathfrak{L}$ internalistically, where propositions are conceived of as the mentalistic meanings of sentences. This might somehow corresponds to the view that possible worlds are mind-dependent objects (*cf.* [Ros$_0$90,Kri$_1$72]). The entities of the isomorphic neuronal algebra may then serve as the "cortical meanings" of a simple semantically compositional, set-theoretic (or predicative) language. The closeness value could be interpreted as a putative distance between a believer and a proposition. If $c([p]^N)$ equals 1 for the brain of the subject, we could say that the subject fully believes or grasps the proposition $[p]^L$.

Thirdly, an interpretation of $\mathfrak{L}$ as an algebra of mental symbols is still not precluded. In this case, propositions are regarded as truth-valuable combinations of mental symbols. This might somehow correspond to the Carnapian [Car$_1$47] view that possible worlds are nothing but state descriptions. The only concession we have to make is that those mental symbols are no longer combined by concatenation. For, the commutation of mental symbols –commutation is the only way to produce equivalencies in $\mathfrak{L}$– must lead to identical propositions in order to guarantee the isomorphism. If $[a = b]^L$ and $[b = a]^L$ were not identical propositions, this would conflict with the fact that $[a = b]^N$ and $[b = a]^N$ are identical brain states. The closeness value $c([p]^N)$ may be interpreted as the degree to which the subject's brain realizes the truth-valuable mental symbol $[p]^L$.

Finally, let me compare oscillatory networks with Turing-style and connectionist architectures. Cognitive models can be distinguished along three features: (i) *Trees:* There are operations from ordered sets of argument representations onto target representations. (ii) *Constituency:* For every tree, its argument representations are constituents of its target representation. (iii) *Order:* For every target representation, there is a determinate order among its constituents.

In standard languages, there are trees, words are constituents of phrases, and the words follow a determinate word order. We can now ask which of the three principles a given cognitive model realizes. Turing-style computers realize all three because they build complex representations from primitive ones by concatenation. Integrated connectionist/symbolic architectures only realize trees. Oscillatory networks, however, realize both trees and the principle of constituency, but not the principle of order.

Oscillatory networks lie in some sense in between classical and connectionist architectures. They resemble connectionist networks in many respects: They may serve as associative, content addressable memories. They process information in parallel, are able to learn from examples, degrade gracefully, etc. Still, oscillatory networks are stronger than traditional connectionist networks because in oscillatory networks primitive representations are constituents of complex representations. The primitive representations determine the causal properties of the complex representations and, thereby, determine their semantic properties. Oscillatory networks unite the virtues and avoid the vices of classical and connectionist networks. They may subserve semantically compositional and systematic representational capacities.

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