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High- vs Low-Level Cognition and the Neuro-Emulative Theory of Mental Representation

Commentary on Peter König, Kai-Uwe Kühnberger, and Tim C. Kietzmann

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König et al. (this volume) in conjunction with König and Krüger (2006) analyze a long-standing and unresolved issue in cognitive science: The relation between low- and high-level cognition. Low cognitive processes include the stages of different perceptual modalities, whereas high-level processes include planning, reasoning, believing, and so on. From the neurophysiological point of view, those systems are based on different networks that correspond to functionally defined cortical regions. However, it seems undeniable that lower perceptual and higher cognitive systems interact. A typical example of a process that occurs at a perceptual stage and communicates with high-level systems is object recognition. During this process, the visual system (i) perceives invariants, i.e., it represents an object as being the same even if perceived from different points of view; and (ii) it subsumes objects that share similar features, for example, different dog instances under the same category: DOG. This representation at the visual level serves as the basis for further higher cognitive processes. From the fact that one recognizes a particular animal as a dog, one can infer a multitude of other facts and events: for example, that this particular dog is not a dangerous one.

The interaction between low- and high-level cognition calls upon the question on whether those systems share similar processes and structures. König and colleagues' core argument is that low- and high-level cognitive systems implement similar structures despite their functional differences. According to the model, the similarity of structure relates to the statistics of the received inputs and the strong relations of perceptual and cognitive systems to action. This approach combines the following assumptions: Neurons in visual areas have sparse activations and are feature specific. They compute the slow temporary changes of an object in order to represent its identity over time. The model purports to explain object representation on the basis of the stability of the input. However, as König and colleagues notice, when subjects represent an object, they often represent this object and its related affordance. An affordance is a property of an object that allows a subject to perform an action upon that object in a way specific for the object (Gibson, 1977). For example, the perceived affordance of a chair may be 'sitable'. Affordances may differ depending on the perceiving subject or situation: The same chair that is suitable to sit for a human adult may be perceived as 'climbable' by a child or by an adult in a different context (e.g., when using a chair to reach an object). These differences may account for the fact that different individuals across and within different species perceive the world in different ways. Moreover, the representation of affordances is at the root of the ability of an individual to predict and support the sensory consequences of actions. For example, regardless which type of ball is in front of you, you will know that every time you kick a ball, that ball will move in a specific direction. The sameness of behavior when faced with similar stimuli can be described in terms of how the subject learns to generalize predicting the action's consequences and thereby learns to select an appropriate action.

According to König and colleagues, the generalization occurring during object recognition – subsuming different instances of the same object under the same category and predicting the consequences of our actions over all instances of the same category – is a process similar to the drawing of an analogy. Analogy is a well-studied high-cognitive phenomenon defined as the transfer of knowledge from known examples to unseen examples in order to make the right classification. For instance, an analogy commonly used in science is to compare electrical circuits to hydraulic systems. Sensory systems, like the visual system, might draw inferences from a known scenario to an unknown one in a similar way. In fact, the generalization of invariants and performed actions allows the subject to predict the behavior and perceive the function of newly perceived objects if those objects resemble some of the objects that have already been categorized. Further, it is claimed that a similar mechanism might be at the basis of very simple analogies and that higher cognitive analogies may have a sensory basis. According to the discussed approach, in the course of perceptual analogy representations within the same category will activate similar neuronal groups. For, the objects of a group – e.g., the objects falling under the category BALL – share some aspects. However, those representations also differ to a certain extent between one another. This might depend on the context of the action and the perceived affordance of an object.

Various approaches on the link between low- and high-level cognition highlight the sensory basis of higher-cognitive representations (for a review, see Barsalou, 2008). The pivotal question is what perceptual and higher-cognitive systems share. König and colleagues stress their similarities in terms of representational resources and their structure. We argue that their model based on objective function and the representation of affordances explains something more: It also accounts for the distinction between attributive and substance concepts.

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The difference between lower-level sensory representations – prior to object recognition – and higher-level cognitive representations – presupposing object recognition – can be accounted for in terms of the difference between the use of thick substance concepts at the later stage of perceptual representations and that of thin attributive concepts at earlier stages. On the one hand, substance concepts represent stable features, invariant over time, which are governed by the conditions of object identity. For example, a banana no longer falls under the substance concept BANANA when it has been smashed. On the other hand, attributive concepts represent variable features, in the sense that an object can fall under different attribute concepts at different times. For example, an object can have different colors at different times. Substance concepts are typically expressed by concrete nouns – in English by names of individuals like *mama*, names of kinds like *mouse* and names of stuffs like *milk*. Attributive concepts, in contrast, are typically expressed in English by adjectives or abstract nouns: *blue*(*-ness), warm*(*-th), lucid*(*-ity*). (Millikan, 1998; Werning, 2008, 2010)

The perspective to be developed here largely draws on the theory of neuro-frames (Werning and Maye, 2007). The theory of neuro-frames holds that (i) substance concepts are decomposable into less complex concepts with attributive concepts at the lower levels, that (ii) the decompositional structure of a substance concept can be rendered by a recursive attribute-value structure, that (iii) the neural realization of a substance concept is distributed over assemblies of neurons and meta-assemblies thereof, that (iv) those neurons pertain to neural maps for various attributes in many afferent and efferent regions of the cortex, and that (v) object-relative neural synchronization is an appropriate mechanism for binding together the distributed information into the neural realization of the substance concept.

Frame theory provides us with a universal account not only for categorization and its link to action-control, but also for the decomposition of concepts. Frames are recursive attribute-value structures. Attributes assign unique values to objects and thus describe functional relations. The values can be structured frames themselves. A frame is defined for a large domain of things and contains a fixed set of attributes (e.g., color, form, flavor), each of which allows for a number of different values (red, green, etc.). The attributes in question are not constrained

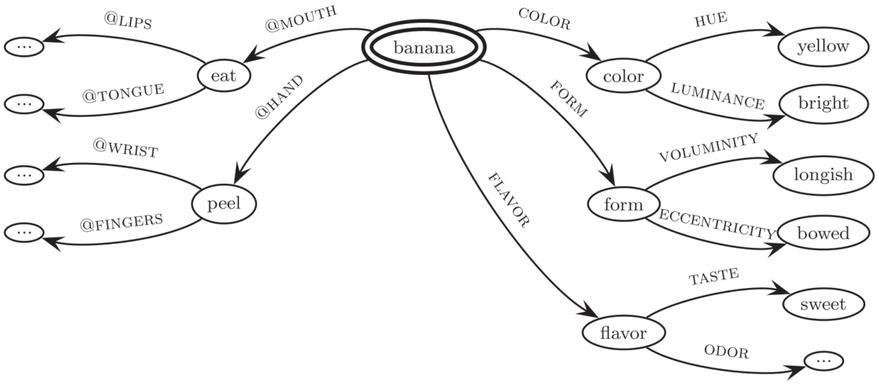

Figure 1: Hypothetical fragment of the frame for the concept BANANA. The substance concept to be decomposed is marked by a double-circle as the referring node of the frame. The labeled arrows denote attributes, the nodes their values. Nodes are themselves regarded as concepts and thus as conceptual parts of the central concept. In English, feature attributes (shown on the right) are frequently lexicalized – their arguments typically enter possessive constructions like *The color of the banana is yellow* or *The banana has the color yellow*. Based on linguistic and neurobiological evidence, we assume that affordances often relate to body parts and hence use the convention "@ + body part". Formally, attributes are mappings from domains of some type into domains of some other type. Petersen and Werning (2007) provide an explicit account of frames using a calculus of typed feature hierarchies and incorporating typicality effects.

to perceptual modalities, but may involve attributes of motor affordances as well. Frames can be nested hierarchically and mutual constraints between attributes (e.g. between states of an object and actions directed to it) and between larger frames can be incorporated. Our model postulates neuro-frames as neuronal bases for concepts.

For many attributes involved in perceptual processing one can anatomically identify cortical correlates. Those areas often exhibit a twofold topological structure and justify the notion of a feature map: (i) a receptor topology (e.g., retinotopy in vision, somatotopy in touch): neighboring regions of neurons code for neighboring regions of the receptor; and (ii) a feature topology: neighboring regions of neurons code for similar features. With respect to the monkey, more than 30 cortical areas forming feature maps are experimentally known for vision alone (Felleman and van Essen, 1991).

Motor attributes may also be parts of frames and appear to have cortical correlates, predominantly in the premotor and motor cortex (Werning, 2010). The cortical organization of motor control with regard to the effectors follows similar topological principles as the cortical organization in perception with regard to the receptors. The discovery of the so-called canonical motor neurons in the mirror neuron system, activated by the sight of an object to which a certain action is applicable (Rizzolatti and Luppino, 2001; Rizzolatti and Craighero, 2004), may provide a basis to integrate affordances into frames. Figure 2 shows a number of neural maps that relate to various attributes of frames.

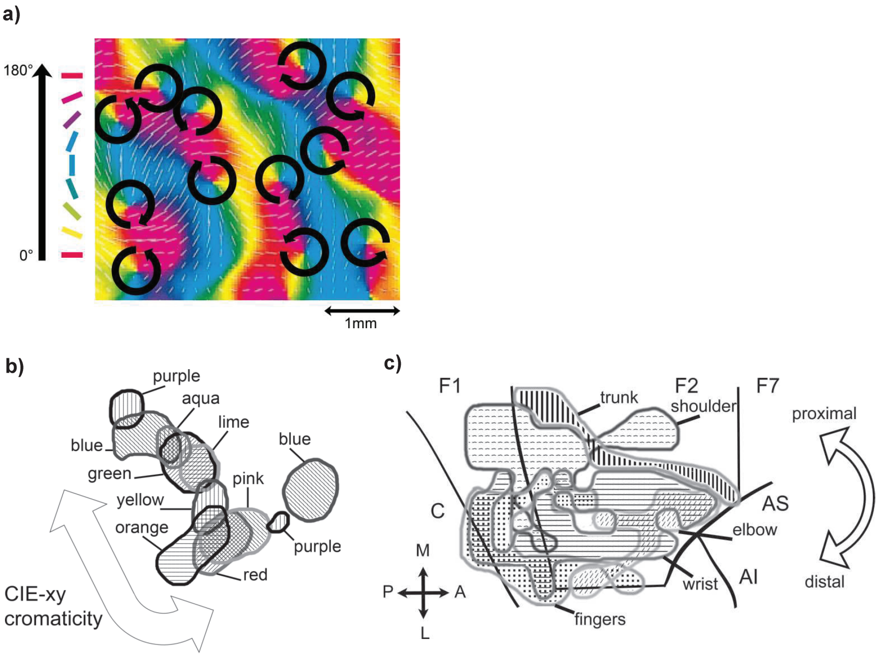

Figure 2: Cortical realizations of frame attributes.
a) Fragment (ca. 4mm²) of the neural feature map for the attribute orientation of cat V1 (adapted from Shmuel and Grinvald, 2000). The arrows indicate the polar topology of the orientation values represented within each hypercolumn. Hypercolumns are arranged in a retinotopic topology.
b) Color band (ca. 1 mm²) from the thin stripes of macaque V2 (adapted from Xiao et al., 2003). The values of the attribute color 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 color bands of V2 is retinotopic.
c) Neural map (ca. 250 mm²) of forelimb movement in macaque primary motor (F1) and dorsal premotor cortex (F2, F7) (adapted from Raos et al., 2003). The overarching topology is somatotopic from proximal to distal movement as shown by the arrow. Due to the size of the region one may expect it to comprise maps for more specific motor attributes. C: central sulcus, AS and AI: superior, respectively, inferior arcuate sulcus.

Canonical neurons are involved in mechanisms for recognizing object affordances and carrying out the semantic knowledge about the object (Sahin and Erdogan, 2009). Hence, the activation of the mirror system brings its multimodal neurons to respond not only to action performance, but also to visual, auditory, somatosensory and proprioceptive signals. This suggests that related processes are grounded functionally by multimodal circuits (Gallese and Lakoff, 2005; Rizzolatti and Sinigaglia, 2010). In particular, the intraparietal sulcus and inferior parietal lobule are involved in multisensory integration and vicarious sensory-motor activations (Rizzolatti and Sinigaglia, 2010; Ishida et al., 2010; Rozzi et al., 2006; Bremmer et al., 2001). These regions, able to receive visual input, are directly connected with each other and with the somatosensory cortex (i.e., BA2; Lewis and van Essen, 2000; Pons and Kaas, 1986) integrating tactile and proprioceptive stimuli as well as containing shared sensory-motor representations (Keysers et al., 2010). These multimodal circuits exhibit some basic semantic features. The activation of a specific action concept, e.g. expressing an affordance or any other motor attribute, induces the activation of the multimodal neural circuits (Pulvermüller and Fadiga, 2010).

The fact that values of different attributes may be instantiated by the same object, but are processed in distinct regions of cortex is a version of the binding problem: how is this information integrated in an object-specific way? How can the color and taste of a banana be represented in distinct regions of cortex, although they are part of the representation of one and the same object?

A prominent and experimentally well supported solution postulates oscillatory neural synchronization as a mechanism of binding: Clusters of neurons that are indicative of different properties sometimes show synchronous oscillatory activity, but only when the properties indicated are instantiated by the same object in the perceptual field; otherwise they are firing asynchronously. Synchronous oscillation, thus, might be regarded as fulfilling the task of binding various property representations together to form the representation of an object having these properties (Singer, 1999). Using oscillatory networks as biologically motivated models, it could be demonstrated how the topological organization of information in the cortex by mechanisms of synchronization may yield a logically structured semantics of concepts (Werning and Maye, 2007; Maye and Werning, 2004, see figures 3 and 4). Compositionality theorems have been provided (Werning, 2005). Oscillation functions play the role of object concepts. Clusters of feature sensitive neurons play the role of attributive concepts. The experimental findings by Schnitzler et al. (2006) on the essential role of neural synchronization for action control may justify the extension of the synchrony-based neuro-frame approach from features to affordances. It should be noted that the envisaged semantics is one of emulation: the neuronal structure is partially isomorphic to a (model-theoretic) model of the representational content. A concept like BANANA thus interrelates a.o. sensoric and motoric emulations: Having the concept BANANA means being able to emulate what a banana would look, taste, feel, and smell like and being able to emulate actions afforded by a banana. Triggering the concept activates the respective sensoric and motoric cerebral regions for the purpose of emulation even in the absence of a real banana. The neuro-frame captures how the various sensoric and motoric emulations are linked to each other. Emulative semantics is a non-symbolic, embodied, but still compositional semantics and might be used to link conceptual resources employed in perception and motor planning to linguistic meaning (Werning, 2012).

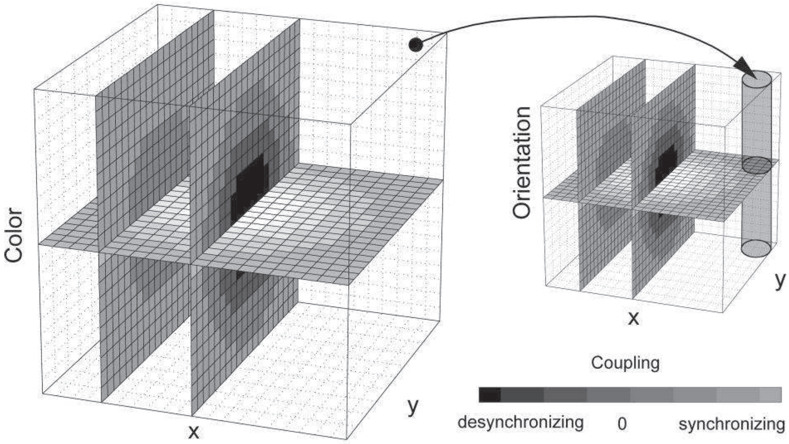

Figure 3: Oscillatory network. The network topology reflects the receptor topology (xy-plane) and the feature topology (z-axis) of the neural maps. Each module realizes one attribute. The layers in each module realize the attribute values. Oscillators activated by neighboring stimulus elements with similar attribute values synchronize (light gray). Oscillators activated by neighboring stimulus elements with unlike attribute values de-synchronize (dark gray). The layers of different modules are connected in a synchronizing way that respects the common receptor topology. (From Maye and Werning, 2007).

Support for the theory of neuro-frames also comes from a number of neuro-linguistic studies. Based on a review of neurobiological data, Pulvermüller (1999) suggests that neural assemblies that pertain to the sensory-motor cortices and are bound by neural synchronization play an important role in understanding the meanings of words and sentences. These cortical sensory-motor action and perception circuits are interdependent in language comprehension. Neuroimaging investigations have shown that perception and understanding of stimuli depend on motor circuits, i.e. specific motor activations can be found when subjects understand speech sounds, word meanings, semantic categories and sentence structures (Pulvermüller and Fadiga, 2010). FMRI studies (Pulvermüller, 2005) regarding the understanding of verbs, e.g., hint at a differential top-down activation of motor and pre-motors areas. We know that the understanding of concrete nouns like *hammer*, for which not only features, but also affordances are salient, results in an activity distributed over the premotor and the visual cortex (Martin et al., 1996; Martin, 2007). The hypothesis that words for substance concepts arouse more widely distributed activity than words for attributive concepts has also been supported by EEG studies (Rappelsberger et al., 2000). Brain areas involved in motor control contribute to neural networks in which verb representations are grounded, e.g. studies on motor deficits such as Parkinson disease reveal impairment of patients' action naming (Rodríguez-Ferreiro et al., 2009). Higher-order abilities such as thinking or linguistic concept use are based in sensory-motor abilities. The relation to attentional mechanisms has been studied by Tacca (2010). Parallels to cases of synaesthesia where hyperbinding within neuroframes might play a role have been discussed by Mroczko-Wąsowicz and Werning (2012).

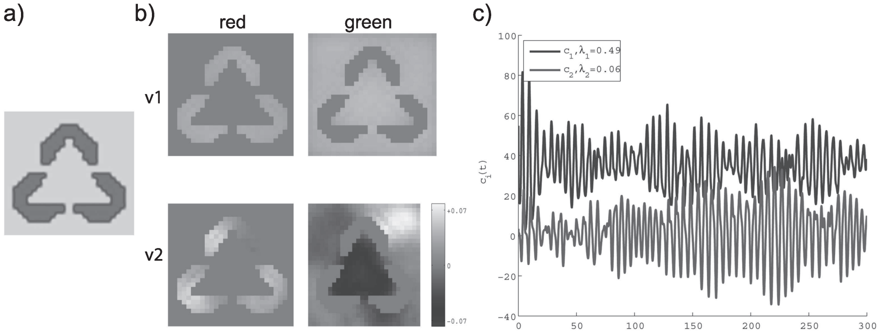

Figure 4: An oscillator network with a single module for color with layers for red and green is stimulated with the Kanizsa illusion. a) Stimulus: three red circle segments on a green ground. b) The two strongest eigenmodes of the network dynamics $\mathbf{v}_1$ and $\mathbf{v}_2$, each subdivided according to layers, are shown. The signs of the vector components are indicated by shades of gray: light gray: positive, middle gray: zero, dark gray: negative. c) Temporal evolution of the two eigenmodes are given by the characteristic oscillatory functions $c_1(t)$ and $c_2(t)$. The eigenvalues $\lambda_{1,2}$ yield the relative contribution of each eigenmode to the overall variability of the network dynamics. Semantic interpretation: The first eigenmode does not render figure ground segregation. The second eigenmode, however, renders a representation of the illusionary triangle (object concept: $-c_2$) as distinct from the background (mostly zero) and the united circle segments (object concept: $+c_2$).

3 Conclusions

We argue that König and colleagues' model, which highlights the optimization of feature selectivity and feature predictability, may also contribute to the explanation of a further property of high- and low- level processes: The distinction between substance and attributive concepts. Neuroframe theory gives a detailed account of how substance concepts – presupposed for higher cognitive processes – and attributive concepts – hosted by lower perceptual cortical areas – relate to each other. The relation is one of recursive conceptual decomposition. Due to the interaction between affordance and feature attributes, neuroframes are flexible enough to allow for a situational dependency when it comes to feature selection. While attributive concepts specify volatile properties of objects, substance concepts are governed by the identity conditions of objects and thus warrant a stable identification of those objects. Since neuroframes capture how substance and attributive concepts relate to each other a situation dependent way they enable an optimization of predictability.

A main idea in philosophy is that if perception and cognition interact, they need to have the same type of representational content, or if they do have different types of content, one needs to further explain how their contents relate. Our hypothesis is that representations at the cognitive level involve conceptual representations (substance concepts) that derive from the recombination of primitive attribute concepts that occur at earlier stages. König and colleagues instead argue that the differences in the final make-up of the representation between low- and high-level cognition account for those systems to implement distinct kinds of content. A hallmark of conceptuality is that representations combine in a compositional fashion. As we noticed above, the recombination of attributive perceptual and motor representations into substance concepts satisfies the principle of compositionality. Hence, we argue that those representations have conceptual content, even if they are not symbolic representations, but emulations.

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