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Morphodynamical enaction: the case of color

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DYNAMICAL COGNITION

With Francisco Varela's death, one of the most beautiful minds I ever met has gone to heaven. The inspired way he succeeded in synthesizing cognitive neurosciences, dynamical models of global brain activity and the phenomenological dimension of consciousness was truly amazing and wonderful. His scientific production was constitutive of a spiritual vocation.

In science, each generation has to tackle some critical problems whose correct scientific formulation is already a challenge. For our generation, one of the primary challenges will have been to naturalize the mind and the intentionality of consciousness using:

1. the empirical results of integrative, cognitive, and computational neurosciences,
2. the mathematical tools for modeling self-organized complex structures.

Today, with the fantastic development of neuromimetic models, dynamical perspectives have become widely accepted – and even dominant – in many fields of neuroscience. We have quite forgotten how difficult it was to develop them thirty years ago in the context of the functionalist symbolic paradigm.

One thing that is particularly striking in Francisco's scientific trajectory is the astonishing and marvelous permanence of his fundamental choices. He saw the dynamical perspective as essential from the beginning. In his final years, it culminated in very interesting works concerning large scale synchronization phenomena and global binding in the brain. In some cortical areas, such as V1 in the primary visual cortex, the synchronization coding the spatial coherence of the percept is well established (e.g. by the experiments of Gray, Singer, König, etc.). But when we look at the mathematical models of synchronization of elementary oscillators (Kuramoto, Daido, Ermentrout, Kopell, etc.), we find that the synchronization process is too slow. In conjunction with Heinz Schuster and Michel Le Van Quyen, Francisco showed that oscillators of Hodgkin-Huxley type or, more simply, of Fitzhugh-Nagumo type, which present bursts of activation, can be synchronized quickly.

Francisco also worked hard, especially with Evan Thompson, on the problems concerning filling-in processes. He strongly emphasized the integration of the different modular processings in the brain through large scale binding. For him, the holistic character of brain dynamics was essential.

At the espistemological level, Francisco was one of the major defenders of the dynamical and enactive approaches as alternatives to the classical functionalist symbolic one. He rejected the thesis that only syntactic structures could be realized at the causal physical level and that semantic structures were therefore epiphenomenal. According to him, these conceptions were not plausible at the neural level and, as he said, were separated from their «biological roots.»

I think that Francisco believed that classical cognitivism only could describe competences (roughly in a Chomskyan-

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Fodorian sense) in a syntactic way, using explicit formal rules, and that its philosophical mistake was to try to endow such descriptions with an explicative power while explanations must be causal and can concern only performances.

Another of Francisco's strong criticism against classical cognitivism concerned its strong representationalist theses. The most critical point was the dogmatic assumption that only a predefined world can be represented. On the contrary, according to the enactive perspective, the properties that are relevant for a cognitive system do not preexist, but rather are produced by the interaction between the system and its environment. It is the coupling which enacts the external world, thus making it meaningful for the system.

I would now like to reflect upon a technical paper that Francisco wrote in collaboration with Evan Thompson and Adrian Palacios (Thomson et al, 1992) on color: «Ways of coloring: Comparative color vision as a case study in cognitive science.»

ON COLOR

By using the term 'enactive perception,' the authors seek to move beyond the traditional conflicts expressed by the following antinomies:

(i) computational objectivism vs. neurophysiological subjectivism,
(ii) external objectivity vs. internal cognitive processing,
(iii) recovering objective properties vs. constructing enacted properties,
(iv) heteronomous input-output systems vs. autonomous self-organizing systems.

They develop two main arguments from external irreducibility and from perceiver relativity. More precisely, their purpose is «to offer a new empirical and philosophical perspective on color vision» (1992:1) using a concept that would simultaneously be experientialist (not objectivist) and ecological (not subjectivist). After having presented the classical theories of color with their 3D color space (hue, saturation, brightness) and their phenomenological hue-opponency (Red/Green, Yellow/Blue), they analyze the neurophysiological and psychophysical correlates and the covariance between phenomenal and biological properties.

Let S be a colored surface with current point s. We have the map $R{:}\rightarrow S\Delta$, $s \rightarrow R(s)$ of S to the space Δ of color channels (the 3 types of cones). But, due to the post-receptor color channels, particularly the opponent chromatic channels R/G, Y/B, and the non-opponent achromatic channel White/Black, we have in fact a composed color map $C(s) = MR(s)$, where M is the post-receptor transformation.

To generate color constancy, one has to disentangle in the irradiance of the visible surfaces the illumination and the reflectance. It is a difficult and technically ill-posed problem of inverse optics whose solution requires the introduction of *a priori* constraints concerning models of light and reflectance, as well as segmentation processes, etc.

The core of Francisco's paper, however, is epistemological and looks for a way to break with the objectivist/subjectivist antinomy. Owing to the species variability of color channels (some species are tetra- and even penta-chromats), it is impossible to identify perceived color with spectral reflectance. In fact, as was well established by neurophysiological experiments and phenomenological eidetic description, the segmentation of visual scenes into different patches and the construing of perceived objects themselves are perceiver-relative. It is a constitution in the strongest phenomenological sense (see Petitot, 1999). Moreover, an argument of external irreducibility adds to this argument of perceiver-relativity. The hue-opponency belongs to the experience of color but lacks any objective physical counterpart. Nevertheless, the alternative of physicalist objectivism cannot be for all that a radical subjectivism which would amount to a sort of neurophysiological solipsism.

The antinomy is formulated by the authors in the following way (p. 21).

Thesis: «The distal world can be specified independently of the animal; it casts images on the perceptual system whose task is to recover the world appropriately from them.»

Antithesis: «The perceptual system projects its own world and the apparent reality of this world is merely a reflection of internal laws of the system.»

The solution, of course, must be sought out in theories of adaptation, evolution and co-evolution. But this is not sufficient. We are also committed to adopt an active conception of perception as an action-driven process. This enactive conception has a Gibsonian orientation, but is immune from the direct realism so prejudicial to Gibson's own ecological approach.

An organism and its environment are evolutionarily co-determined, and the problem is «to specify the sensory-motor patterns that underlie the visual guidance of animal activity in its local situation» (Thomspon et al 1992:22). In the case of color, it is to understand the relational, rather than the purely objective or purely subjective essence of this phenomenal quality.

MORPHODYNAMICAL MODELS

We will now explain how morphodynamical models can formulate this relational essence. For that, we must pay enough attention to the mathematical problems of modeling. We will show that the simplest mathematical models that can explain perceptive situations naturally include a solution to the antinomy.

Let us adopt first an «objectivist» computational point of view according to which the cognitive task of the visual system is to recover 3D visual scenes from highly ambiguous 2D projections. Let V be a visual scene consisting of visible surfaces moving in 3-space R^3. It is a highly difficult problem to understand how the geometrical information about V is encoded in the optical signal. Indeed, this information is essentially embedded in the qualitative discontinuities (QDs) as the apparent contours of shapes, and we must therefore understand how discontinuities can be encoded in and transported by solutions of the wave equation.

At the retinal level, V is projected to a bidimensional pattern $I(x,y)$, and the problem of inverse optics is to recover V from $I(x,y)$. In order to perform this difficult computational task, the visual system must solve two different inverse problems: one geometrical and the other qualitative.

The geometrical inverse problem consists of recovering the shapes of the objects from their apparent contours. For this, the visual system must (at least) be able to:

(i) detect the QDs embedded in $I(x,y)$;
(ii) detect among them those who share an *objective* meaning;
(iii) interpret some of these objective QDs as apparent contours of shapes;
(iv) reconstruct the shapes from these contours.

Regarding (i), it is now quite certain that the retinal ganglion cells perform a wavelet analysis of the signal. Wavelet analysis is a local and multi-scale Fourier analysis that is able to extract the QDs (and therefore geometrical information) from the signal. As David Marr (Marr, 1982) has pointed out, this analysis is performed by convolution with ganglion cells whose receptive profiles are Laplacians of Gaussians. «Marr's conjecture» was solved by Stéphane Mallat (Mallat-Zhong, 1989): it is possible to reconstruct $I(x,y)$ from the QDs provided by wavelet analysis.

Regarding (ii), the criterion for a QD to be objective is that it can be detected at an entire range of different scales.

Regarding (iii) and (iv), it is a very deep mathematical problem that can be solved only using singularity theory (Whitney, Thom, Arnold, see Petitot, 1990).

The solution of the geometrical inverse problem therefore leads to a geometrical configuration (W,K), where W is the spatial extension of the visual scene V, and K is a set of *QDs*.

And what about the qualities that fill in the different domains of W delimited by K? Let's suppose that we still accept the computational objectivist perspective. If we restrict ourselves to a single quality, namely color, we would make the hypothesis:

(i) that at each point w of W there is a well-defined (objective) value $R(w)$ of the reflectance of the surfaces in V;
(ii) that $R(w)$ varies continuously (and even differentiably) as a function of w, except along K;
(iii) that the perceptual quality of color $C(w)$ encodes $R(w)$.

But the key point is that perception, from retinal transduction to post-receptors color channels, converts the reflectance $R(w)$ into the perceptual quality of color $C(w)$ in a more complex way than a mere encoding.

In fact, the situation is the following:

(i) We can interpret (W,K) as either objective or subjective data because retinotopy is well preserved up to the primary visual cortex and there are isomorphisms between the retina and cortical layers via neural maps.
(ii) $R(w)$ and $C(w)$ covary but belong to different spaces, respectively R (reflectance) and Q (quality).
(iii) If we consider the fiber bundles $W\text{x}R \to W$ and $W\text{x}Q \to W$ (projections of Cartesian products on their first factor) we get sections:

R: $w \in \to W(w,R(w)) \in W\text{x}R$ of $W\text{x}R \to W$ and C: $w \in W \to (w,C(w)) \in W\text{x}Q$ of $W\text{x}Q \to W$ which are discontinuous along K.

The fundamental problem is to understand the relationship σ between $R(w) \in R$ and $C(w) \in Q$. Indeed it is the dramatic misunderstanding of σ that is at the origin of the antinomy:

(i) for the objectivist, $C(w)$ is a mere encoding of $R(w)$, and σ can be neglected because it reduces to an isomorphism between R and Q;
(ii) for the subjectivist, $C(w)$ is irreducible to $R(w)$, and σ can't be a simple map grounding objectivism.

The solution to this version of the antinomy is that, as a color space that can be interpreted in sensorial (color channels), phenomenal (hue, saturation, brightness) or neurological (perceptual contents = neural states) terms, Q is an internal space of the perceptual system S while the values $R(w)$ are external stimuli.

The first key remark is that there is no direct correspondence $R(w) \to C(w)$ but only a triggering of an internal state $C(w)$ by the stimulus $R(w)$: $C(w)$ is a dynamical response of the system S to the stimulus $R(w)$. The hue-opponency property is a characteristic aspect to this fact.

The second key remark is that such internal perceptual states are attractors of some internal dynamics. All the material the authors bring to bear concerning the global computations, the structure of hues, the ago-antagonism of color-channels and the self-organization of the system of colors is mathematically expressible by the fact that color qualities (hues for instance) are attractors of an internal self-organizing dynamics X defined on the internal space Q. Q and X are of course highly species-dependent while R is objective.

The discontinuous sections $C(w)$ are then the result of a complex dynamical process. In fact, we get a field X_w of internal dynamics controlled by W, and $C(w)$ is the attractor of X_w which is *selected* and actualized by $R(w)$. Then, $R(w)$ is a control parameter for X_w and $W\text{x}R$ is a control space. In such a morphodynamical model, the qualitative discontinuities of K are recovered as dynamical events of bifurcation: at the crossing of K, the attractor selected by $R(w)$ bifurcates toward another attractor and, consequently, $C(w)$ presents a QD.

We see that the relationship s between $R(w)$ and $C(w)$ has nothing to do with a mere map between simple spaces. It is in fact the composition of (at least) four processes:

(iii) an objective map $W \to R$, $w \to R(w)$;
(iv) a field of dynamics σ: $W \to X$, $w \to X_w$, embedding the extension W of the visual scene V in the functional (infinite dimensional) space X of internal dynamics X;
(v) a selection process selecting, according to the objective input $R(w)$

and general laws of selection, an attractor A_w of X_w ;

(vi) a phenomenological display of A_w as the phenomenal qualia $C(w)$.

Morphodynamical models can be implemented in neural networks and synthesize computational objectivism and neurophysiological subjectivism.

(i) There is no longer a conflict between the thesis that the color-system detects the reflectance and the antithesis that it constructs a specific response to reflectance. $R(w)$ selects (as a control parameter) an attractor $C(w)$ and this is a construction. But, as far as $C(w)$ is causally determined by $R(w)$, $C(w)$ is an index for $R(w)$ and then detects $R(w)$.

(ii) The constancy of color and its role in the segmentation derive from the structural stability of the attractor $C(w)$ relatively to the variations of $R(w)$. By definition, the fundamental dynamical property of structural stability implies qualitative constancy. In that sense, it is true that $C(w)$ cannot be an exact (quantitative) coding of $R(w)$. But, nevertheless, $C(w)$ recovers $R(w)$ in a qualitative sense.

(iii) It is true that the physical reflectance space R does not share the same type of properties as the color-space Q. The main difference is that there are no dynamics on R. In that sense, subjectivist thesis is essentially right: we cannot type-identify the chromatic sensory states from the stimuli. But the argument must be refined substantially: even if perceptual states cannot be functionally type-identified 'by the (distal) properties they have the function to detect' (Thompson, et al 1992:10), they can nevertheless be determined by these properties as far as they are controlled by them.

We see how the two main arguments of the authors can be deepened. Regarding the argument from external irreducibility it can be emphasized that external reducibility relies upon the confusion between the stimulus $R(w)$ and the attractor $C(w)$ it selects, that is to say between the external control of the internal self-organizing dynamics X_w and the internal state it determines. Therefore, the criticism raised by the authors against objectivism is essentially correct. However, the attractor $C(w)$ is a canonical response of the system to $R(w)$. If it is conceived of morphodynamically, the stimulus-response schema is no longer contradictory with a self-organization process.

With respect to the perceiver-relativity argument, we can emphasize that, if it is true that colors «contribute to the task of segmenting the visual scene into regions of distinct surfaces and/or objects» (p. 17), it is because bifurcations of hues take place along the QDs of K and therefore contribute to the task of recovering K. But this does not mean that segmentation itself is essentially species dependent. The QDs of K are objective geometric entities.

The morphodynamical approach of enactive perception shows how to synthesize computational objectivism and neurophysiological subjectivism: in morphodynamical models, recovering the environment as a pre-specified distal world is exactly the same as constructively enacting it. When external inputs control internal self-organizing dynamics, a heteronomous input-output system becomes equivalent to an autonomous self-organizing system. This confirms the theoretical necessity of an experientialist, ecological, and enactive conception of color, based on the evolutionary principle of «the codetermination of perceiving animals and their environments» (p. 20). It is true that, as was already emphasized by Levins and Lewontin (1983) , «organisms transduce the physical signals that reach them» and that «the significance of these signals depends on the structure of the organism» (Thompson, et al 1992: 21). But in fact these two fundamental properties are shared by every sufficiently complex system that can respond to external stimuli by dynamically generating internal states.

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