Neural representation of sensory data

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February 5, 2002
(printed on: February 7, 2002)

Abstract

In Mental Imagery: In Search of a Theory, Pylyshyn revives the spectre of the “little green man”, arguing for a largely symbolic representation of visual imagery. To clarify this problem, we provide precise definitions of the key term “picture”, we present some examples of our definition, and we outline an information-theoretic analysis suggesting that the problem of addressing data in the brain requires a partially analogue and partially symbolic solution. This is made concrete in the ventral stream of object recognition, from V1 to IT cortex.

1 What is a “picture”??

The core problem with the “picture theory” is the lack of a definition of the key term “picture”. A more correct term has been suggested earlier (Schwartz, 1980)– computational anatomy, the properties of locally regular feature maps. The “little green man” problem is clarified by noting that:

- No known feature maps are isometric. They do not preserve metric information. They are “distorted”, but
- The lack of metric structure is irrelevant to their potential semantic content. There is no “little green man” to be confused by the (distorted) non-isometric maps of the brain. There are only neuroscientists looking inwards– and, if they wish not be confused by what they see, they have only to learn about existing mathematical accounts of the feature maps of the brain. Figure 1 and Figure 2 are two examples. But the neurons of the brain, “looking” at feature maps from within, have no such problem!
2 Neural computation: a definition

Definition 1 (Neural computation) Neural computation, as with all computation, is based on a correct (i.e., expedient) choice of data structure and algorithm. Neural feature maps can be viewed as a form of data structure. There is little to say about neural algorithms at present--no one has ever observed a non-trivial neural network in vivo--but there are abundant experimental observations of neural data structures.

Definition 2 (Computational anatomy) Patterns of topographic mapping and columnar architecture are two prominent forms of (spatial) data structure in the brain. The key requirement is that nearby neurons in a laminar sheet must have trigger features that are nearby in some feature space.

Example 1 (Receptotopic maps of V1, V2, V3, V4, MT, MST, LGN, S. Colliculus, S1, A1, etc.) For receptotopy, the feature space is $\mathbb{R}^2$, e.g., the retinal surface, the body surface, or the cochlear surface. See Figure 1 for an example of human V1, V2, and V3.

Figure 1: (a) "Retinal" view of US Naval Academy, high resolution. (b) Model of V1-V2-V3 complex, produced as a single dipole map function (?). The dipole map is a direct generalization of the familiar log-polar model of V1 topography (Schwartz, 1994). V1 is the central "ovoid" region, V2 is the first surrounding "ring" and V3 the outer "ring" of cortex. (c) The USNA image is mapped via the complex dipole map to create an image model of the V1-V2-V3 complex. A face in a window of the USNA (a), which is visible in the original high resolution image, is clearly seen--repeated three times in the foveal representations of V1, V2, and V3. The entire campus of the USNA is compressed, via the highly non-linear cortical magnification factor, into the para-foveal and peripheral regions of the image. This figure represents only the topographic aspects, not the ocular dominance, orientation map or other spatially represented data. The result may look confusing to a neuroscientist observer, but we believe that the brain has little problem interpreting this complex spatial data structure.

Example 2 (Orientation columns in V1, direction columns in MT) The feature space is $\mathbb{P}^1$ (V1) and $S^1$ (MT), orientation and direction, respectively. The target space is V1 (or MT), the "pinwheel" pattern of orientation (or direction) tuning. The pinwheel structures result from the singularities associated with the different topological structure of the feature space and the cortical target (Schwartz and Rojas, 1991; Wood and Schwartz, 1999).

Example 3 (Ocular dominance columns in V1) The feature space is a (double-sheeted copy) of a visual hemi-field ($\mathbb{R}^2$). The target mapping is interlaced via a proto-column construction (see Landau and Schwartz, 1994) to a locally regular map of the two half-fields, as shown in Figure 2.
Figure 2: Mapping a stereo-pair (a), (b) into a model of V1 layer IV ocular dominance columns. The disparity is represented as a visual “echo” or offset of repeating image elements. A non-linear cepstral filter extracts the stereo disparity in the form of a subsequent spatially mapped representation (Yeshurun and Schwartz, 1989) (see the prototype model of (Landau and Schwartz, 1994)).

Pylyshyn briefly mentions the existence of topographic structure in V1, but omits mention of the (approximately) 30-40 other visual topographic areas, as well as the other sensory modalities. Furthermore, he omits columnar structure entirely from this discussion. The neo-cortex is largely organized in terms of feature maps and that these features maps are potentially semantic.

3 Information Cost of Addressing Symbols

Pylyshyn’s key unstated assumptions is clear from his “null hypothesis”: ...reasoning with mental images involves the same form of representation and the same processes as that of reasoning general...

We agree that reasoning about pictures may well use the same processes as reasoning in general. The problem here is the unstated assumption that “reasoning in general” is symbolic. But, do we really know that reasoning is itself not mediated by spatio-temporal representations, i.e., a “picture theory” of reasoning? There appears to be an implicit assumption in parts of the cognitive science community that computation is symbolically mediated. We will now present an argument in support of the idea that anatomy as data structure is an unavoidable consequence of the high cost of “addressing” symbolic data in the brain.

Recently, Rieke et al. (1998) demonstrated that the spike sequence of the H1 neuron of the fly is a temporal replica of the sensory stimulus. There are only two H1 neurons in the fly brain, for for each side. They call this idea “flynculus”. This does not seem like a good candidate for “symbolic” coding. The fly uses time to code time, not symbols to code time. Time is free, and the fly is short on neural space. The semantic meaning of an H1 spike is, in part, the time that it occurs.

The parallel is clear: attaching a spatial label to a spike in V1 is potentially expensive. There are about $10^5$ resolvable spatial locations in the human visual field (see (Rojer and Schwartz, 1990) for derivation) – 17 bits. The semantic content of a spike in V1 is probably no more than 2-5 bits. The obvious solution is to use physical space to code visual space. Progressing from V1 to V2 ... and on to IT, the spatial precision becomes lesser and the semantic content of a spike becomes greater. It is expedient to pay the price for a symbolic code (i.e., axons, labeled lines, “grandmother cells”). It seems that one feasible solution for spatial coding of visual stimuli is a gradual transition from a largely (but not completely) spatio-temporal code near the periphery (i.e., V1, V2, ...) to a largely (but not...
4 Summary

In our analysis, we have not addressed the issue of “imagery”. It seems obvious that the real issue is visual representation, and the first area that needs clarification is the representation of visual stimuli, not mental re-creations of them.

Behavioral-level experiments are impotent, in principle, to address questions of neural representation. Purely symbolic and purely analog “machines” can easily mimic each other at the behavioral level.

If the brain is really the symbolic processor that Pylyshyn seems to envision, then it certainly has an inordinate fondness for “pictures”.

References


