Authors' Response

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For the authors' responses to comments similar to those expressed here by **Balsam & Drew**, please see: M. Domjan, B. Cusato, & R. Villarreal (2000). Extensions, elaborations, and explanations of the role of evolution and learning in the control of social behavior. BBS 23(2):269–82. [Authors' Response to first round of commentary.]

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Commentary on **Mike Page (2000). Connectionist modelling in psychology: A localist manifesto. BBS 23(4):443–512.**

Abstract of the original article: Over the last decade, fully distributed models have become dominant in connectionist psychological modelling, whereas the virtues of localist models have been underestimated. This target article illustrates some of the benefits of localist modelling. Localist models are characterized by the presence of localist representations rather than the absence of distributed representations. A generalized localist model is proposed that exhibits many of the properties of fully distributed models. It can be applied to a number of problems that are difficult for fully distributed models and its applicability can be extended through comparisons with a number of classic mathematical models of behaviour. There are reasons why localist models have been underused, though these often misconstrue the localist position. In particular, many conclusions about connectionist representation, based on neuroscientific observation, can be called into question. There are still some problems inherent in the application of fully distributed systems and some inadequacies in proposed solutions to these problems. In the domain of psychological modelling, localist modelling is to be preferred.

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The local is running on the express track: Localist models better facilitate understanding of nervous system function

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Abstract: Artificial neural networks have weaknesses as models of cognition. A conventional neural network has limitations of computational power. The localist representation is at least equal to its competition. We contend that locally connected neural networks are perfectly capable of storing and retrieving the individual features, but the process of reconstruction must be otherwise explained. We support the localist position but propose a "hybrid" model that can begin to explain cognition in anatomically plausible terms.

Whether they use localist or distributed representations, artificial neural networks as they are currently conceived have a serious weakness if they are able to be applied as models of natural cognition. It is well known from anatomical and physiological studies that neurons have a finite connection range beyond which the probability of connection of two cells decreases exponentially. This range is about 250 μ in the visual cortex (Krone et al. 1986) and 400 μ in the hippocampus (Traub et al. 1988). On the other hand, neural networks are constructed so that almost all cells in a given layer are connected to all the cells in some other layer. This situation could only be approximately applicable if all the cells fell within a single connection range. Using the figures of Wilson and Cowan (1973), about 10,000 cells could fit within a cylinder of radius of one connection length and thus constitute such a locally *connected* network.

In contrast, the cortex of the edible frog has about 6 million cells (Wilson & Cowan 1973). Making all allowances for the efficiency of scientifically constructed learning algorithms compared with what has been contrived by nature, it is not likely that a conventional neural network operating under the constraints of brain anatomy could have computational power greater than that of a frog. This is not to detract from the demonstrated abilities of neural networks whose nodes and/or activation states are given semantic significance; we simply question their direct relevance to animal psychology.

For the purposes of this discussion, we accept the arguments of the author that the localist representation is at least equal to its competition. The first question we must ask is how much information an actual neuron can store. There might very well be a "grandmother cell" because of the childhood implantation, but it is highly unlikely that anyone other than immediate family has a "Mike Page" cell. Yet we are capable of recognizing numerous relative strangers, largely through the reconstruction of distributively stored details (Bartlett 1932). We contend that locally connected neural networks are perfectly capable of storing and retrieving the individual features, but the process of reconstruction must be otherwise explained.

A rat negotiating a maze, for example, has memory known to be implanted through the action of single hippocampal "place" and "direction" cells (Muller et al. 1996; Rolls et al. 1998). The choice of direction at any point, however, must be assembled from this stored fragmentary data. Of particular significance is the recent work of Fried and colleagues (1997) who measured the activity of single hippocampal neurons during recognition tests. They found that some neurons responded differentially to faces and inanimate objects, some to different emotional expressions, and some to combinations of expression and gender. This would be, in our opinion, the right amount of content a node of an anatomically constrained localist neural network could hold.

What mechanism can connect the elementary localist networks? Perhaps a network that takes Euclidean distance into account can be devised. None exists as far as we know, so questions about how ability is degraded by systematic incompleteness of connections cannot be answered. There have been some simulations incorporating connection range (Krone et al. 1986; Traub et al. 1987; 1988; 1989), but these have not been given any cognitive content; rather, they are concerned with the general behavior of the neural medium.

This area of study was first suggested by Wilson and Cowan (1973), who created what can be called a continuum theory of neural tissue. The differential elements of this medium contain many cells; in modern terms they can be called *neural networks,* although such terms as "cell assemblies" (Hebb 1949) or "groups" have been applied. These elements may or may not be functional wholes; their constituent cells might change with task. However, it is logical to give each, at any time, the computational abilities of a localist neural network.

According to the theory, the elements are interconnected by probabilistically distributed connections of type e-e, e-i, i-e, and i-i, between (literal or figurative) "excitatory" and "inhibitory" "cell" species. The existence of e-e connections signifies an internal source of (electrochemical) energy, so that the medium can support growing disturbances. The conditions of growth give rise to waves with sharply defined wavelength spectra (Koch & Leisman 1990; 1996; 2001; Leisman & Koch 2000). The preferred wavelengths are controlled by the synaptic parameters, and they are always significantly longer than the largest average synaptic connection range.

We postulate that this phenomenon provides a mechanism by which the active nodes of the elementary networks can be "connected." Unlike a neural network, the connection is not causal; instead, two nodes are simultaneously active when the distance between them is an integral multiple of the favored wavelength, which can be changed by changes in the state of the relevant brain region.

We have applied this concept to models of the brain stem, cortex, and hippocampus (Koch & Leisman 1990; 1996; 2001; Leisman & Koch 2000). The last studies are of particular interest for the present discussion. The growth properties of hippocampal waves change as synapses are modified by Hebbian conditioning (Hebb 1949; 1972). Such a process exists in the hippocampus (Eccles 1986), manifested by strengthening in synapses between geometrically and synaptically neighboring cells. This is certainly akin to local weight modification in neural networks, but it has important global effects. Not only does it change the nature of the waves from decay to growth, but it also controls the amplified wavelength and therefore the connections among the networks.

Hence our title: The local ultimately ramifies throughout cognitive regions. We hope to see in the future a "hybrid" model that can begin to explain cognition in anatomically plausible terms.

Local versus distributed: A poor taxonomy of neural coding strategies

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Abstract: Page is to be congratulated for challenging some misconceptions about neural representation. However, his target article, and the commentaries to it, highlight that the terms "local" and "distributed" are open to misinterpretation. These terms provide a poor description of neural coding strategies and a better taxonomy might resolve some of the issues.

Consider a neural network in which individual nodes represent single letters of the alphabet. When a letter is presented to this

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