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A NOTE ON *HOW WE KNOW UNIVERSALS*

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While *A Logical Calculus of the Ideas Immanent in Nervous Activity* is the most cited of McCulloch's papers, and lies, with Turing's (1936) analysis of effective computation, at the heart of modern automata theory, I believe that this other major fruit of his collaboration with Walter Pitts is McCulloch's most significant contribution to brain theory, for in it we see the interplay of daring theory and vigorous experimental evidence.

Before turning to a brief outline of the paper, it is worth noting that it was written before the introduction of microelectrodes revolutionized neurophysiology by allowing experimenters to monitor the electrical activity of single neurons. One of the classics of single-cell neurophysiology [Lettvin et al. (1959)] is acknowledged to be an outgrowth of *How We Know Universals*, even though the processes found in frog tectum are not those predicted for mammalian cortex.

The paper has two parts, each addressing the question of how we may recognize an object despite drastic changes in size, rotational displacement, or position. The first half suggests that we internally apply a whole set of transformations to features of the sensed object, and average over the resulting ensemble to extract "invariants" that allow the brain to characterize what *type* of object is being sensed. This theory does not seem to have been confirmed, but did provide ideas on feature detectors that, as suggested in the previous paragraph, have become an important part of neurophysiology.

The second part addresses the problem by suggesting how a pattern might be brought to "standard form", as when the direction of gaze is shifted to fixate the "center of gravity" of an image.

The model of the superior colliculus presented by Pitts and McCulloch is important because it stresses that

> (a) an important method of coding information in the brain is by *topographically* organized activity distributed over *layers* of neurons
>
> (b) computation may be carried out in a distributed fashion by a collection of neurons without the intervention of a central executive.

The resultant view of the brain as an "action-oriented layered somatotopically organized distributed computer" has seemed to me to be central to cybernetics (Arbib [1972]). Although McCulloch [1945] coined the term *heterarchy* to refer to circular value-orderings, it is now more often used for the style of control structure of (b) above. This style has one of its most interesting exemplifications in the work of Kilmer and McCulloch on the reticular formation, reprinted elsewhere in this volume. For an up-to-date counterpoint of theory and experiment of collicular function, the reader may consult Didday and Arbib [1974], Wurtz and Goldberg [1972] and McIlwain [1973].

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