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EDITORIAL

Binding and Consciousness

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The binding problem is, basically, the problem of how the unity of conscious perception is brought about by the distributed activities of the central nervous system. The problem, however, appears in several different formulations, and some of them are silent about the role of consciousness. In visual neuroscience the problem can be crystallized in the following question: How do all the thousands of anatomically separated neurons responding to different parts or features of the same stimulus integrate their activity into a neural representation of one single object? In cognitive science, the question can be expressed this way: How does the information initially processed by a multitude of independent modular systems become integrated into coherent representations for perception, memory, and action?

These formulations of the binding problem, however, do not explicitly mention consciousness. What makes binding of special interest for consciousness research is, of course, the experiential unity of consciousness: in subjective visual perception, objects appear as unified perceptual wholes located in one unified perceptual world. The phenomenal unity apparent in subjective visual awareness should, for all we know, be somehow related to the brain's cognitive and neural mechanisms of binding. Discovering those mechanisms might significantly increase our understanding of how the phenomenal unity of consciousness is brought about in the brain. A theory of binding would thus represent a major advance in the naturalistic explanation of consciousness.

The binding problem is not an entirely modern invention. The core of the problem was seen long ago by Immanuel Kant, although he did not use the term ‘‘binding.’’ He thought that the world we experience is above all a world of perceived objects, and in order for the mind to produce such a complex and unified representation, the mind has to have some way to relate the different things it experiences to one another. He called this activity of the mind ‘‘synthesis’’; we now call it ‘‘binding.’’ In the

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history of experimental psychology, the Gestalt school dealt with issues closely related to the binding problem, describing sensory organization in terms of perceptual units. These units are formed in the subjective perceptual field when the contents of particular areas are experienced as ‘‘belonging together’’ and thus the perceptual units become segregated from their environment. The Gestaltists tried to explain these effects by referring to holistic fields in perception and in the brain. Köhler (1957) even attempted to record ‘‘brain currents’’ from human and animal subjects when visual objects were shown to them. Thus, the Gestalt psychologists did both theoretical and empirical research on the binding problem and even tried to test their ideas in the spirit of cognitive neuroscience; unfortunately, the time was not ripe for such an approach.

THE “40Hz HYPOTHESIS”

Modern formulations of the binding problem were introduced in connection with, e.g., Treisman’s feature integration theory of attention (Treisman, 1988, 1996), Damasio’s (1989) theory of neural convergence zones, and models for synchronous firing in neural networks (von der Malsburg & Schneider, 1986). However, the first authors to explicitly connect neurocognitive binding with a theory of consciousness were Crick and Koch (1990). In their paper *Towards a Neurobiological Theory of Consciousness* they wrote:

> . . . seeing any one object often involves neurons in many different visual areas. The problem of how these neurons temporarily become active as a unit is often described as ‘‘the binding problem.’’ (p. 269)

Their hypothesis as to how binding might be effected was, in a nutshell,

> We suggest that one of the functions of consciousness is to present the result of various underlying computations and that this involves an attentional mechanism that temporarily binds the relevant neurons together by synchronizing their spikes in 40 Hz oscillations. . . . objects for which the binding problem has been solved are placed into working memory. (p. 272)

Empirical evidence for the presence of such oscillations in the mammalian cortex had started to accumulate at the end of the 1980s. The major findings from human and animal studies are reviewed in the present special issue by Engel, Fries, König, Brecht, and Singer and by Sauve. In addition to Crick and Koch’s theory, Singer (1994) and Llinás and Paré (1996) have put forward hypotheses about the connection between consciousness and 40Hz synchronization. Each theory emphasizes slightly different mechanisms in the generation of synchronous oscillations and coherent contents for awareness: Crick and Koch stress the role of a serial attentional mechanism and speculate that thalamocortical feedback pathways may play a part in bringing about the synchronized oscillations. Llinás and Paré theorize that the 40Hz oscillations are generated in two types of thalamocortical loops, one activating the sensory fragments of experience, the other generating a ‘‘temporal context’’ serving in binding the fragments together. Singer’s theory postulates that specific intracortical synchronizing connections between cells are the primary source and realizer of synchronized activity among cortical cells. It is not entirely clear whether these different views are actually incompatible, for all of them do assign at least some role to both intracortical and thalamocortical connections, although the emphasis and details within each theory are different. Interestingly, members of Engel's group report finding significant enhancement of ''stimulus specific'' 40Hz oscillations in the visual cortex during stimulation of the reticular formation (Munk, Roelfsema, König, Engel, & Singer, 1996), implicating subcortical arousal and attention in binding. In a 1994 paper, Singer suggested that

> . . . it is possible that access to the level of processing where representations reach consciousness is gated by coherence. It may be that the only activation patterns that reach the threshold of conscious awareness are those that are sufficiently organized or coherent. (Singer, 1994, p. 101)

In the present special issue, the target paper by Engel et al. offers a full explication of this coherence hypothesis. Its central postulate is that some kind of neural binding mechanism is critical for the establishment of conscious states. According to the authors of the target article, there is ample evidence that one basic aspect of consciousness, sensory awareness, requires neural synchronization: only information coded by an ensemble of synchronously firing neurons can be selected for access to visual awareness. Sauve agrees with the postulates of the target article and in his article reviews additional empirical evidence for the hypothesis.

ALTERNATIVE VIEWS

Although Engel et al. and Sauve review an impressive amount of empirical evidence in support of the connection between neural synchronization and phenomenal consciousness, the hypothesis is far from universally accepted in the research community. This is clear in the critical commentaries elicited by the target article. These range from philosophical and theoretical critiques analyzing, for example, what it really means to claim that something is a necessary condition for consciousness (Gold, Hardcastle, Kurthen, & Smythies) to issues about whether the recent empirical evidence is as convincing as Engel et al. would like to believe (Vanni). After all, not all studies have found evidence of synchronization.

In their article, Zeki and Bartels develop a competing theory of consciousness and binding that rejects the view advocated by Engel *et al.* Instead, they argue that visual consciousness is, by its very nature, modular: i.e., elementary visual sensations are generated in autonomous processing systems, each possessing a ''microconsciousness.'' In their view, large-scale neural coherence is not necessary for isolated conscious sensations to arise, and binding need not be synchronous. It remains unclear how these modular microconsciousnesses ''add up'' to provide the overall unity of phenomenal consciousness; but then, the authors do not seem to believe that any such highlevel binding is necessary.

Finally, Revonsuo and Newman and Grace argue in their articles that present theories, while giving impetus to much empirical research on binding, tend to treat it as a single problem, when in fact there are a set of related problems, some of which clearly refer to consciousness, some not. In order to avoid confusion of categories, Revonsuo recommends distinguishing three levels of binding: the phenomenal, neural, and cognitive.

Newman and Grace argue for levels as well, not on theoretical but neuroscientific grounds. While accepting the plausibility of 40Hz oscillations as a mechanism for the rapid perceptual binding of cortical cells, they hold that this is merely a preliminary step in a more extended process whereby such ''bound'' representations become integrated into working memory. Presenting recent evidence concerning the subcortical gating of prefrontal and inferotemporal cortex activities, they hypothesize that a selective, second-order ''gating'' is necessary to integrate such representations (and filter out competing ones) to generate the *stream* of consciousness characterizing working memory. Such binding of episodes extends well beyond the millisecond cycles of 40Hz oscillations and may be reflected in subcortically driven, synchronous oscillations below 10 Hz.

The variety of papers in this special issue on the binding problem highlights both the rapid progress being made in accumulating empirical data on neural synchronization and visual awareness and the fundamental theoretical disagreements as to what sort of conclusions we should make on the basis of all these findings. Different researchers do not agree on how convincing the empirical evidence for temporal binding actually is. An even more fundamental problem is that the authors of this issue do not even agree to what extent phenomenal consciousness *is* unified in the first place. If the unity of consciousness is an illusion, as, e.g., Dennett (1991) argues, then there is no binding problem to be solved. But even if one grants that argument, at least the illusion of unity needs to be explained. Clearly, the articles and commentaries presented in this special issue offer no ready solution to the binding problem. It is our hope and belief, however, that at the very least they further our understanding of what the problem consists of and how to address it at the different levels of description and explanation involved.

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