

The feature-binding problem is an ill-posed problem

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The binding problem arises when visual features (colour, orientation), said to be coded in independent brain modules, are to be integrated into unitary percepts. I argue that binding is an ill-posed problem, because those modules are now known to code jointly for multiple features, rendering the feature-binding issue moot. A hierarchical reentrant system explains the emergence of coherent visual objects from primitive features. An initial feed-forward sweep activates many high-level perceptual hypotheses, which descend to lower levels, where they correlate themselves with the ongoing activity. Low correlations are discarded, whereas the hypothesis that yields the highest correlation is confirmed and leads to conscious awareness. In this system, there is no separate binding process that actively assigns features to objects.

The feature-binding problem

In the everyday world, we perceive objects as coherent, unified wholes. Yet, it is thought that the visual brain is subdivided into independent modules (see [Glossary](#)), each specialized in processing a different feature, such as colour, orientation, form, or motion. The binding problem deals with the question of how the outputs of these independent modules are brought together and integrated so as to yield the perception of a unitary, integrated visual world.

First identified as a theoretical problem by von der Malsburg [1], the binding problem is rooted in the widely acclaimed discovery of neurons in primary visual cortex that were found to respond selectively to single features, such as colour or orientation [2–4]. Any given incoming image – for example, a vertical red bar and a horizontal green bar – was said to be decomposed into those independent modules, causing the relationship among stimulus features to be lost. The binding problem arises when those disconnected features need to be recombined so as to yield a veridical representation of the original stimulus. In our example, the output of the red colour module needs to be bound with the output of the vertical – not the horizontal – orientation module.

The importance of the binding problem is widely acknowledged. For example, a well-known neuroscience textbook states that ‘the binding problem [...] remains one of the central unsolved puzzles in our understanding of the neurobiological bases of perception’ ([5], p. 567). Many solutions have been proposed. Indeed, entire issues of journals have been devoted to that topic: *Neuron*,

Vol. 24, Issue 1 (September 1999) and, more recently, *Visual Cognition*, Vol. 17, Issue 1–2 (January 2009). A generally agreed-upon solution, however, has proved elusive. In this article, I argue that the feature-binding problem has defied solution because it is based on an erroneous premise and is, therefore, ill-posed.

Feature binding is an ill-posed problem

Although entirely plausible at the time the binding problem was first formulated, the notion of modular specificity and independence has been disconfirmed by advances in neuroanatomy and neurophysiology. Instead of coding for single features, neurons throughout the visual cortex are now known to code for multiple features, thus rendering the binding question moot.

A splendid example of joint selectivity for form and colour has been reported by Mandelli and Kiper [6], who used concentric chromatic Glass patterns similar to those illustrated in [Figure 1](#). A compelling inference from that study is that perception of monochromatic Glass patterns is mediated by neurons in area V4 that are concurrently selective for circular form and red colour or by corresponding neurons selective for circular form and green colour. The important point is that neurons selective for red cannot mediate the perception of green patterns, and vice versa. Thus, perception of the dichromatic image in [Figure 1c](#) is mediated by two distinct populations of neurons, each selective for a different aggregate of random dots from which no circular pattern can emerge.

Glossary

Binding: the dynamic linkage of multiple features leading to the perception of a given object as a coherent, unified whole.

Feature: an irreducible attribute of an object, for example, its colour, orientation, luminance, form, or motion. The perception of these attributes is said to be mediated by specialized modules in the visual system.

Invariant representation: a neural representation of visual information capable of mediating the perception of an input image independently of attributes such as size, contrast, location on the retina, and angle of view. Invariant representations are abstract perceptual categories of objects or scenes whose complexity varies with hierarchical level.

Module: a neuronal assembly in striate or extrastriate cortex that specializes in the processing of a given attribute of an object. Any given module may respond to a single feature or jointly to conjunctions of features.

Perceptual hypotheses: invariant representations coded at relatively higher levels within the hierarchical system. Incoming stimuli trigger several perceptual hypotheses, which then descend through reentrant pathways to lower levels, where they match themselves to the ongoing activity.

Reentrant processing: iterative signalling between regions in the visual brain linked by reciprocal connections. Among the functions attributed to reentrant processing are object recognition through the confirmation of perceptual hypotheses and boosting of the signal-to-noise ratio in the visual representation of the incoming stimulus.

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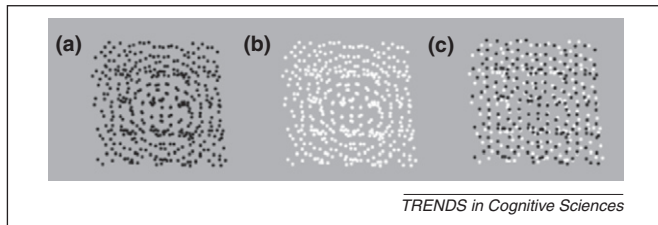


Figure 1. Glass patterns similar to those used by Mandelli and Kiper [6]. The patterns were constructed with an initial aggregate of random dots, a copy of which was rotated and superimposed on the original aggregate. In Mandelli and Kiper's study, the dots were either red or green (rendered here as black and white, respectively). When the image is monochromatic [panels (a) and (b)], the concentric pattern is readily apparent. When the image is dichromatic [panel (c)], the concentric pattern is hardly visible, if at all. Similar results have been reported by Goldfarb and Treisman [7], who found that perception of a Star of David in which the two component triangles were of different colours was impaired relative to one in which the two triangles were of the same colour. The phenomenological appearance of chromatic Glass patterns can be explained in terms of mechanisms in area V4 that are concurrently selective for form and colour. Evidence has been reported for populations of V4 neurons that are selective for various combinations of form and colour [8,9]. Just as cogently, it has been shown that neurons in macaque area V4 (but not V1 or V2) are activated selectively by different Glass patterns [10]. It should be noted that because the images in Mandelli and Kiper's [6] study were equiluminant with the background, perception of the concentric pattern could not have been mediated by luminance-sensitive mechanisms.

This and similar findings [11–14] strongly suggest that, contrary to earlier beliefs, form and colour are processed not in independent modules but in modules that are concurrently selective for combinations of the two features. This obviously does away with the need for feature binding, at least at the level of V4. On the other hand, the alternative has been raised that those V4 neurons may merely code for binding that has taken place at a lower level, such as primary visual cortex [15]. That option is disconfirmed by two considerations.

First, the angular size of the Glass patterns used by Mandelli and Kiper [6] (Figure 1), although easily encompassed within the large receptive fields in area V4, far exceeds the scope of the small receptive fields in primary visual cortex. This is consistent with the finding that neurons in V1 and V2 do not respond selectively to different Glass patterns, as do neurons in V4 [10].

Second, neurons jointly selective for multiple features have been documented in primary visual cortex. For example, Gegenfurtner *et al.* [16] found that most colour-sensitive neurons in area V2 are jointly selective for other features, such as directional motion and size. Notably, over 40% of neurons were jointly selective for colour and orientation. Similarly, Friedman *et al.* [17] found that the majority of colour-selective neurons in areas V1 and V2 were also orientation-tuned. Based on this evidence, Friedman *et al.* pointedly noted that: 'It is time to recognize that early physiological reports [of independent colour and orientation modules] were misleading. [...] a binding problem does not exist for the representation of colour and orientation in the visual cortex.' ([17], p. 610).

The significance of this neurophysiological evidence for the feature-binding problem is unambiguous: stimulus features such as colour and form are not processed in independent modules whose outputs need to be bound together in order to reconstruct the original image. Rather, specific combinations of colour and form are processed jointly by specialized neurons throughout the visual cortex, thereby rendering the feature-binding problem moot.

Beyond feature-binding: processing at higher levels

Removing feature-binding from the list of legitimate problems in early vision leaves us with much the same problem that exercised von der Malsburg: how can unitary, coherent visual objects (e.g., a bowl of fruit) emerge from the disconnected outputs of units in primary cortex? On the face of it, this might be done by adapting Feature Integration Theory (FIT) to handle the outputs of neurons selective for more than one feature in much the same way as the theory currently handles the outputs of neurons selective for single features. But this option encounters much the same difficulties that beset the current version of the theory [18] (Box 1).

This said, it is fitting to question the overall conceptual framework in which the binding problem has been couched. The mainstay of that framework is a visual system in which primitive features need to coalesce – or be bound together – in order for perceptual objects to emerge into consciousness. Here, I propose an alternative in which, instead of coalescing to form perceptual objects, primitive features are the basic units of information against which high-level perceptual hypotheses are compared and correlated. This is done through iterative reentrant processing.

Ontogeny and structure of a reentrant system

It has been known for some time that communication between brain regions is seldom one-way. If a source area sends signals to a target area, then the target area sends signals back to the source area through reentrant pathways

Box 1. Feature Integration Theory (FIT) and the concept of 'attention'

At the core of FIT are two distinct stages of processing [19–21]. In the first (preattentive) stage, the visual input is decomposed into primitive features, such as colour and orientation, that are registered in independent modules arranged in retinotopic maps. In the second (attentive) stage, attention intervenes and acts as glue that binds together features and locations to form perceptual objects. FIT has attracted considerable interest, but it has been criticized for its vague treatment of the concept of attention.

Attention is usually described as a limited resource used for selecting aspects of the visual world that are relevant to the task at hand. More specific definitions include a filter [22], a spotlight [23], a zoom lens [24], as well as glue [19]. A major drawback of these metaphors is that they do not specify what underlying mechanisms mediate the purported function. For example, as pointedly noted by Tsai [25], FIT does not specify the processes by which the attentional glue binds features into objects. The same can be said for the other metaphors. These considerations place obvious limits to the usefulness of attention as an explanatory tool.

The usefulness of the concept of attention has been questioned at a more general level by Chun, *et al.* who noted that 'Attention has become a catch-all term for how the brain controls its own information processing...' ([26], p. 74). Rather, they argue that the term 'attention' should be treated like other general terms, such as 'memory', as connoting a broad range of phenomena that are probably mediated by different mechanisms. In the domain of memory, these would correspond to various forms of memory, such as iconic memory and procedural memory. In the domain of attention, they would correspond to different basic functions of attention, such as selection, modulation, and vigilance. From this perspective, concepts such as 'spotlight', 'zoom lens', and 'glue' cannot be regarded as legitimate accounts of the phenomena they purport to explain. At best, they are labels for whatever known or unknown processes mediate those phenomena; but they can also be an impediment to communication and understanding.

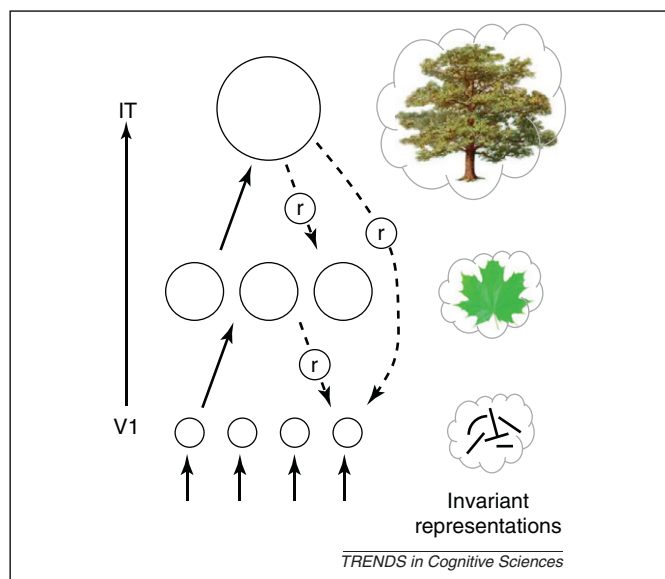


Figure 2. Schematic view of a reentrant system's architecture. For simplicity, only three levels are illustrated: the low level corresponds broadly to primary visual cortex (V1), the middle level to extrastriate cortex, and the top level to higher brain regions, such as inferotemporal cortex (IT). In practice, the system has many more levels [27]. The system's basic unit is the cell assembly [30], which is formed when more than two neurons are involved in a firing sequence. Consider three neurons connected in such a way that the firing of neuron A activates neuron B, which then activates neuron C, which finally activates neuron A again. Suppose that the firing of neuron A is triggered by the sight of a given object. Repeated presentations of that object – or of other objects that share critical features with it – will cause repeated firing of neuron A and its attendant network (neurons B and C). This will strengthen the connections linking the neurons in that network and, in turn, increase the probability that the entire network will be activated again in the future. Cell assemblies are formed at all levels of the hierarchy, and their contents vary with the type of information that is processed at that level. Thus, in primary visual cortex cell assemblies code for aggregates of simple features, whereas at the level of IT they code for entire objects. Hawkins [31] has made a case for regarding cell assemblies as encoding invariant representations that are activated when relevant objects are presented. The concept of invariant representation differs from that of a template in that it is more abstract and detail-free. Invariant representations correspond to perceptual categories whose complexity varies with hierarchical level. They can be thought of as akin to Plato's ideal forms. In the present example, the invariant representation of a leaf does not correspond to any specific leaf; rather, it represents an abstract and detail-free concept of 'leafness'. The important consideration is that each unit beyond the lowest level contains invariant representations of the information that is coded in greater detail but lesser generality in the units located at lower levels in the hierarchy.

[27,28]. A comprehensive outline of the neurophysiology of reentrant connections has been presented by Bullier [29] as the basis for an integrated model of visual processing. An example of such a system is illustrated in Figure 2, which outlines the system's neural connectivity, its ontogeny, and some of its functions.

Once established, such a hierarchical system constitutes a vast repository of memories in the form of neural networks that make up a model of the world. Those networks are used in cortical reentrant loops to set up moment-to-moment action plans that serve not only for identifying objects, but also for predicting the temporal course of environmental regularities (e.g., the trajectory of a ball flying through the air) and learned behaviour sequences (e.g., the sequence of actions involved in starting your car).

Functioning of the system

In the system illustrated in Figure 2, perceptions arise from iterative exchanges between brain regions linked by

two-way pathways. The initial feed-forward sweep (solid arrows) activates a large number of invariant representations throughout the system, culminating in the triggering of a set of perceptual hypotheses in inferotemporal cortex (IT) that are in some ways consistent with the sensory input. In a study that combined magnetoencephalography and functional magnetic resonance imaging, Bar *et al.* [32] showed that recognition-related neural networks ("perceptual hypotheses" in the present context) in temporal cortex can be primed via faster activation of orbitofrontal pathways triggered by the low spatial frequencies in the image. The perceptual hypotheses primed by the feed-forward sweep then descend through reentrant pathways (segmented arrows in Figure 2) to lower levels, where they attempt to match themselves to the pattern of ongoing activity through a process of correlation (encircled *r*'s in Figure 2). Matches that yield low correlations are discarded, whereas the hypothesis that yields the highest correlation is confirmed and eventually leads to conscious awareness (see Box 2).

No need for binding

In such a reentrant system, there is no separate binding process that actively assigns features to objects. Rather, the information coded in primary visual cortex acts as an 'active blackboard' for the perceptual hypotheses sent back from higher regions. According to Mumford [33,34], all the perceptual hypotheses triggered by the feed-forward sweep are compared in parallel with the information at the lower level. If an appropriate match is not found in the first pass, the outcome of the comparison is sent back to higher regions to start a new iteration. In Mumford's model, additional iterations result in dynamic modification of the prevailing perceptual hypothesis by means of a relaxation algorithm. This iterative-looping sequence culminates in the confirmation of the perceptual hypothesis

Box 2. Variants of hierarchical reentrant systems

Several variants of the reentrant system illustrated in Figure 2 have been proposed. Among them are the memory-prediction model [31], the computational model of cortico-cortical loops [33,34], adaptive-resonance theory [35], the ALOPEX optimization model [36], the reverse-hierarchy model [37], the neuronal model of the attentional spotlight [38], and the object-substitution model [39]. The common thread linking all these models is that perceptions emerge from comparisons between the contents of high-level neural networks and the ongoing activity triggered by the input at lower levels. The models differ as to the neural locus of the comparisons. Mumford [33,34] points to the thalamus as the likely site, whereas Hawkins [31] favors the primary visual cortex. One possibility is that correlations are carried out throughout the system, as illustrated in Figure 2.

The circuitry and logical gating required for correlating two signals is readily available in the visual cortex [31,33,40–44]. As summarized by Hawkins [31], cells in layer 4 of area V1 (where signals arrive from lower regions) project to layers 2 and 3, as do cells from layer 1 (where reentrant signals arrive from higher regions). Thus, both ascending and reentrant signals meet in layers 2 and 3, where they can be correlated by forming the inputs to a third neuron that performs a logical AND operation. Notably, many neurons in layers 2 and 3 project to the input layer of the next higher region. Those projections could carry the outcome of the correlations – performed in layers 2 and 3 – between reentrant perceptual hypotheses and the ongoing activity triggered by the incoming stimulus.

that best fits the input data. Conscious awareness of the initial stimulus then follows.

Implementation of Mumford's [33,34] relaxation algorithm enables the perception not only of everyday objects, but also of strange and unusual stimuli, such as the purple giraffe with wings mentioned by Treisman [15]. An obvious prerequisite for such a perception, of course, is that invariant representations of giraffes and wings have been established in earlier experiences with those and similar objects, probably through Hebbian learning.

Illusory conjunctions

Phenomena usually explained in terms of the broad – and somewhat nebulous – concept of 'attention' (Box 1) are explained naturally within an iterative reentrant framework. Illusory conjunctions are a case in point. First studied by Treisman and Schmidt [45], illusory conjunctions occur when features are combined incorrectly to form an illusory object. For example, the colour of a red square may be erroneously attributed to that of a green triangle. The likelihood of illusory conjunctions is known to increase as a function of several factors, including the similarity of the features in the search display [46] and their spatial proximity to one another [47]. The observer's set also plays a role: the incidence of illusory conjunctions in a given search display depends on the observer's expectation [48].

Within FIT, illusory conjunctions are attributed to failures of the attentional glue to bind the correct features (but see Box 3). The empirical findings noted above are explained in terms of attentional malfunctions. For example, it is harder to focus the attentional spotlight on any given item when there are other items nearby, especially if they resemble one another. Similarly, the wrong features may pass an attentional filter that has been set inappropriately by the observer's expectation.

Box 3. Reentrant accounts of feature binding

Recent work on the binding problem has been couched in the context of reentrant processing. Bouvier and Treisman [49] employed common-onset masking [39] to show that visual feature binding requires reentry. Braet and Humphreys [50] reached a similar conclusion in a study in which transcranial magnetic stimulation delivered over occipital or posterior parietal cortex, at a stimulus-onset asynchrony set to coincide with the reentrant sweep, caused a significant increment in illusory conjunctions. In both cases, however, reentry is said to merely confirm or consolidate binding that had taken place beforehand in primary visual cortex. This, of course, does not offer a solution to the binding problem. At any rate, the neurophysiological evidence discussed in the present article shows that there is no binding of low-level features to be consolidated. Consistent with that evidence, there is no binding issue to be explained within the hierarchical reentrant system proposed here.

Solutions to the binding problem that do not engage reentrant processes have also been proposed. These include connectionist models [51] and feed-forward models involving cascades of reflexive computations [52,53]. The alternative has also been considered that object recognition may be mediated by either reentrant or feed-forward processes, depending on the circumstances. For example, objects whose representations are firmly established in IT may be recognized accurately upon the feed-forward sweep alone, without a reentrant check. This option is buttressed by the finding that an unfamiliar task that initially requires reentry can be performed accurately on the feed-forward sweep alone once learning has occurred [54].

Within a reentrant framework, illusory conjunctions are attributed to failures of the correlational process. For example, among the reentrant perceptual hypotheses, one that does not match the real world may gain the highest correlation and, therefore, be confirmed. This is likely to occur more frequently when the items are crowded or easily confusable with one another, or when a perceptual hypothesis has initially (but incorrectly) been given greater weight by the observer's expectation (e.g., if you expect to see a snake in the grass, you can easily mistake a twig for a snake).

Clearly, the reentrant-processing model and FIT offer different accounts of illusory conjunctions and of the attendant empirical evidence. The FIT account is problematic because it is predicated on the now-disconfirmed premise of independent feature modules. Moreover, different attentional metaphors need to be invoked to account for the pertinent findings. In contrast, the iterative reentry model offers a coherent account based on a single principle: the correlation between reentrant perceptual hypotheses and ongoing activity at the lower level.

Concluding remarks: feature binding, then and now

In this article, I have argued that seeking a solution to the feature-binding problem is futile, because the problem is ill-posed. What is yet to be solved, however, is the related problem of object perception, which I suggest may be approached in terms of iterative reentrant processing.

The current literature reveals two main trends. In one, perhaps in tacit acknowledgment that the problem defied solution, binding has been redefined to encompass a broad range of phenomena. For example, in the introduction to a special issue on binding in the journal *Visual Cognition* it is stated that 'the binding problem is a ubiquitous one that applies to perception, attention, working memory, and long-term memory systems.' ([55], p. 1). Individual contributions to that special issue reflect this broad scope [56–59]. This, in my opinion, is not a good idea. Given that different instances of 'binding' in perception, attention, and memory are unlikely to be subserved by one and the same mechanism, using a single term to denote them all is likely to lead to the kind of confusion associated with the term 'attention' discussed in Box 1.

In the other main trend, binding is generally viewed as a problem of pattern perception, with research focusing on the underlying neural circuitry [12,14,18,52,53]. Of principal interest in this work is the reciprocal connectivity between regions that correspond broadly to the bottom and middle layers in Figure 2. In one such implementation [42,44], low-level 'border-ownership' neurons are said to interact recursively with higher-level 'grouping' neurons, which structure the information in readiness for further processing. The next step in this approach is to explore the functional connectivity between 'grouping' neurons and higher-level neurons corresponding to the top level in Figure 2.

Regardless of developments in the field, one thing is certain: the feature-binding problem, as originally formulated by von der Malsburg [1], need no longer be of concern. This is because the original assumption of modular independence has now been disconfirmed.

Acknowledgments

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