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On Feature Binding in Space and Time

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ABSTRACT

When presented with a yellow Volkswagen and a red Ferrari, how does the brain figure out which color goes with which car? The binding problem refers to how the visual system pre-consciously combines visual features of objects in the physical world to create coherent mental equivalents in our consciousness. I discuss why feature binding is a problem for our brains despite its seemingly effortless resolution in everyday life. Drawing from experimental cognitive psychology, I demonstrate how it manifests in space and time.

Keywords

Binding Problem, Feature Binding, Temporal Binding

1. INTRODUCTION

The visual world that we are presented with everyday is made up of a bewildering myriad of colors, shapes and sizes. Our brains are well-equipped to prevent sensory overload and separate the ‘wheat’ from the ‘chaff’, as it were, and give meaning to all that we perceive. But this ability is largely unconscious, seemingly instantaneous, above all remarkably efficient. The question of how such unconscious ‘zombies’ in our brains collude to create an ineluctably deep conscious reality in our minds is a long-standing yet unanswered one. Thus, fascinating though the enigmatic nature of Mona Lisa’s smile or the aesthetic beauty of a red Ferrari may be, equally complex and mysterious are the cognitive mechanisms that underlie our conscious appreciation of those qualities.

One of the prominent topics of scientific inquiry into zombies in the brain relates to the question of *feature binding*. Simply put, it is the process by which individual features of a physical object, like color, orientation, shape, etc. must be correctly ‘bound together’ to create its mental representation before it can be consciously perceived. That is to say, before we can ponder the beauty of either Mona Lisa or that Ferrari, the brain needs to be able to correctly put together

the individual parts of her face, as it must do with the lines making up the automobile.

2. WHY IS BINDING A PROBLEM?

Because of the unconscious automaticity of binding in our daily lives, we’re able to deal with the sensory overload with apparent effortlessness. But under appropriate circumstances, the actual processing of visual information that leads up to conscious perception can be experimentally studied by inducing errors in the process, thereby demonstrating the existence of a *binding problem* [4]. The problem itself can be boiled down to a simple question: *When presented with a red circle and a blue square, how does the brain associate redness with circularity, and blueness with squareness, and not the other way around?*. This question is rendered that much more interesting by our knowledge of neuroanatomy elaborated on in the next section, which tells us that information present in different brain regions is drawn together to solve the binding problem. Hence, the problem also serves as an illustration of how processes that are the neural correlates of consciousness in the brain translate electrical activity into phenomenological experience [2].

2.1 Climbing up the Visual Hierarchy

The visual information processing system is architected, in some sense, as a hierarchy of processing layers. The eyes perform the initial processing of light incident on the retina, the output of which feeds up through a succession of layers in the cortex. Neurons in lower layers of the hierarchy are specialized to respond only to specific colors and orientations occurring only in specific regions within our field of vision. Effectively, early visual areas are organized as spatial maps of primitive shapes and forms, where features like color and orientation are loosely bundled together in regions in the visual field. As activity propagates up the hierarchy, neurons in upper layers respond to progressively more complex shapes and objects and represent more complicated structures, but at the expense of spatial detail [3].

But where in this picture of the visual system does binding come into play? It might seem that binding is not really a problem at all, as the spatially localized bundles of features in the early visual areas could be combined into coherent representations in conscious perception. But as visual search experiments have shown, these feature bundles are not distinct enough to subserve conscious experience. As we shall see, evidence from visual search experiments demonstrates that *attention* ‘glues’ together features of physical objects into distinct and detailed mental representations.

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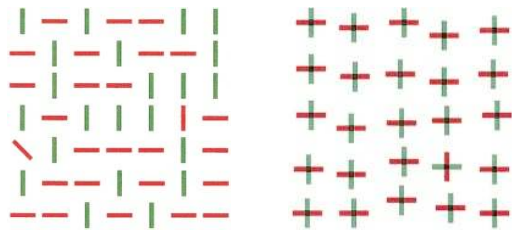


Figure 1: Search for a differently rotated bar (left) and a red vertical bar (right). After [6].

3. THE BINDING PROBLEM IN SPACE

Empirical study has demonstrated the existence of the spatial binding problem, so called because the visual system must correctly bind together the bundles of visual features at different spatial locations in our field of vision. Experimental tests of this phenomenon usually employ a *visual search* paradigm, where participants search for a specially designated target object amongst a collection of distracting objects displayed on a screen. Over two decades of experimentation have shown that we're very good at detecting the target if it has a single distinctive feature represented in early visual areas, like either color or orientation. But in contrast, if the target is identifiable only by a distinctive *conjunction* of such features, the task becomes a whole lot harder.

The problem becomes intuitively clear in the sample search arrays in Fig. 1. Finding an oddly oriented bar in the left array is almost instantaneous and effortless. This is because the target bar has a unique feature that makes it 'pop out': its orientation. The proverbial mind's eye is automatically drawn to the target. On the other hand, finding a red vertical bar in the right array takes more work. The mind's eye must 'rove' the array as it is guided to the region likely to contain the target, after which attention must bind together the bundles of colors and orientations to create well-defined mental objects before one of them can be selected. We constantly use this so-called 'spotlight' of attention to selectively filter out irrelevant details and zoom in to salient ones in the world around us. Numerous experiments like this have shown that attention acts as the binding glue that is applied unconsciously to groups of spatial features to solve the binding problem and subserve conscious experience [5].

4. THE BINDING PROBLEM IN TIME

The real world presents us with a dynamic and ever-changing visual environment where stimuli compete for our attention not only in space, but also in time. As the stimuli in our field of vision change continuously, so do the corresponding spatial maps of their features in the brain. In other words, at any given point in time, the features of the stimuli present at a given location in our visual field overlap in time with the features of stimuli presented before and after it at that location. Consequently, the binding problem has a temporal dimension to it, because in order to combine stimulus features into coherent representations in our conscious experience, the visual system has sets of temporally overlapping features to pick from.

This temporal variant of the binding problem shows up in experiments that employ a rapidly changing sequence of

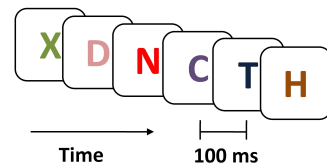


Figure 2: A sample stream of stimuli used in a temporal binding experiment. Participants are required to identify the red letter.

fleeting stimuli, presented one after the other at the same location on a screen. An example of such a stream of stimuli is shown in Fig. 2, where participants must identify a red letter amongst differently colored ones. Unlike in visual search, loose bundles of early visual features in these experiments all occur in the same location in space, and so close to each other in time that people consciously report the identities of letters presented just before or after the target. These errors reflect incorrect bindings called *Illusory conjunctions* [1]. They are mental representations of non-existent physical objects, which to our conscious selves often seem as 'real' as correct bindings.

The data gathered from such experiments is used to inform our understanding of feature binding in the brain. In addition to recording the kind of errors participants make, we can get direct estimates of the dynamics of neuronal activity related to binding processes by recording and analyzing *electroencephalograms* (also called 'brain waves') from participants. These electrical signals are evoked by neurons in the brain as they process visual information, and systematically reflect underlying patterns of neural activity in different regions of the cortex. Analysis of these patterns directly inform the mechanisms by which the binding problem is solved by the brain.

5. CONCLUSIONS

This paper has attempted to make a case for the existence of a binding problem in visual perception, arguing that its study gives us fascinating insights into the neural correlates of conscious perception.

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