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Integrating Perceptual Organization and Attention: A New Model For Object-Based Attention

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Abstract

Recent research shows that, under certain conditions, visual attention is object-based. That is, attention preferentially selects objects in the visual field. These objects are processed, culminating in object recognition. On this formulation, the objects selected by attention are perceptual groups determined by the principles of perceptual organization of Gestalt psychology. These groups are formed independently of attentional processes and conceptual knowledge. This view is not consistent with available data about the visual system, which shows that perceptual organization is sensitive to conceptual information, depends on attentional processes, and infers representations that best explain the visual stimulus. Here, I propose a new account of visual attention that aims to correct these limitations of the Gestalt-based formulation. The nature of the object representations underlying perceptual and attentional mechanisms is discussed. It is proposed that attention and perception interact in an iterative process wherein constraints imposed both by the visual stimulus and an observer's cognitive set determine the "objects" to which attention is allocated. Thus, visual attention is object based precisely because it is intricately involved in perceptual organization, and not because it selects the output of perceptual organization, as is generally claimed. Experimental results that support the claim that attention influences perceptual organization are reviewed. Finally, the implications for human factors research and the metaphysics of everyday objects are discussed.

Introduction

Vision is generally assumed to have the functions of identifying, locating, and directing action towards objects (Solso, 1996). It is also assumed that the visual system requires attentional mechanisms to limit the amount of sensory information it processes (Fernandez-Duque & Johnson, 1999). Thus, awareness of objects in the environment is supposed to result from a series of processing stages that select sensory information and then construct representations of objects by extracting regularities from the visual stimulus and matching them to patterns in memory (Palmer, 1999).

It was first assumed that visual attention selects certain regions of the visual field, much the way a spotlight illuminates part of a stage and leaves the rest in the dark. Accordingly, this model is known as the spotlight model of visual attention (Fernandez-Duque & Johnson, 1999). On this model, attention is first directed to a region of the visual field, and only the information within that region is processed for object identification. This assumption was

questioned when researchers observed that people respond to visual features that belong to a single object more quickly and accurately than when the features belong to two objects (Duncan, 1984; Treisman, Kahneman & Burkell, 1983). Subsequent research confirmed that it is usually easier to process information within a single object than across objects (Lavie & Driver, 1996). These findings have led to the object-based model of visual attention (Duncan, 1984; Lavie & Driver, 1996). It is now generally recognized that the spotlight and the object-based models capture complementary aspects of visual attention (Driver & Baylis, 1998).

It is undeniable that information can be processed more readily within one object than across many (Lavie & Driver, 1996; Driver & Baylis, 1998). However, the object-based explanation for this difference in processing efficiency is problematic. Cognitive psychologists generally distinguish between spatio-temporally bounded physical objects and the mental representations of these objects. Physical objects correspond to what philosophers call concrete particulars (Loux, 1998), and will subsequently be referred to as c-objects. Similarly, the mental representation of visual objects will be henceforth referred to as p-objects (for "phenomenological" objects). The generally accepted story about object perception is that the visual system constructs p-objects, which represent c-objects via various perceptual and cognitive processes. Researchers who accept the object-based model contend that attention selects "objects" for further processing. Which objects are these – p-objects or c-objects? P-objects are supposed to be the end product of visual processing (Solso, 1996), so attention must presumably be engaged prior to the construction of p-objects. However, the alternate claim that attention directly processes c-objects themselves instead of sensory input is nonsense. Most researchers assume the visual system first constructs low-level representations of c-objects, based on the physical properties of the stimulus. These representations are then elaborated into p-objects by higher-order visual and conceptual processes (Hoffman, 1998; Palmer, 1999). These low-level representations will be referred to as a-objects (for "attentional objects"). The object-based model can be restated thus: Visual attention selects a-objects, which are passed on to higher visual processes for elaboration into p-objects, which are representations of c-objects.

Philosophers are actively studying the nature of c-objects (see Loux, 1998) and perceptual psychologists are

researching p-objects (e.g. see Biederman, 1995, and Kosslyn, 1995). But the notion of a-object implicit in object-based attention is still poorly defined. Most researchers take a-objects to be perceptual groupings based on the Gestalt principles of perceptual organization (Driver & Baylis, 1998), according to which observers perceive the details of a scene only as parts of global patterns. Perceptual organization was thought to conform to the general principle of figural goodness, or *Prägnanz* (Koffka, 1935). Figural goodness was exemplified in a number of specific principles (e.g., figure-ground, grouping by similarity, good continuation, closure, and common fate; Palmer, 1999). However, this view of a-objects is inadequate.

Cognitive scientists tend to assume that cognitive processing occurs in discrete stages, as first proposed by Sternberg (1969), until evidence forces them to think otherwise. Accordingly, researchers studying object-based attention have typically assumed that perceptual grouping, in the form of Gestalt grouping, occurs at a processing stage that is independent of, but feeds into, attentional processes, and that the product of attentional selection are independent of, but feed into, object recognition processes (Feldman, 1999). This view is problematic on two counts: first, the evidence that perceptual organization occurs prior to, and independently of, visual attention is not definitive. Second, the Gestalt account of perceptual organization itself has many shortcomings. Let us examine these two issues in turn.

Attention and Perceptual Organization

Mack, Tang, Tuma, Kahn and Rock (1992) and Rock, Linnett, Grant and Mack (1992) have presented results that suggest that perceptual organization does not occur without attention. They had participants perform a task that engaged their attention (typically, judging the relative length of the branches of a cross) while varying the background on which the main stimulus was displayed. Most trials had either a blank or a random background, but each participant also saw three (non-consecutive) trials where the background contained a 'critical stimulus', either a single shape or formed some Gestalt grouping. On the first critical trial, most participants reported not seeing the Gestalt grouping or not perceiving the shape or size of the lone object. On the second critical stimulus trial, participants were generally more successful in detecting the Gestalt group or the object. On third critical stimulus trial, participants were asked to report on the background stimulus only, generally with nearly perfect results.

Mack et al. (1992) and Rock et al. (1992) assumed that on the first critical stimulus trial, participants were not expecting to see anything of import in the background, and thus focused all of their attention on their primary task, whereas on the second and third critical stimulus trials, they implicitly allocated some or all of their attention to the background pattern. Accordingly, they interpreted their results to mean that perceptual organization cannot occur without attention. Ben-Av, Sagi and Braun (1992) reported

a similar study where participants had difficulty identifying background Gestalt groupings as their primary visual task became more demanding.

The results just discussed are not conclusive, however, as they cannot rule out that participants were merely unable to remember or encode the 'unattended' stimuli rather than failing to perceive them at all. Evidence along these lines is provided by Moore and Egeth (1997)¹. In a series of experiments, they had subjects judge the relative length of two parallel horizontal lines while varying the background. On half the trials the background consisted of random black and white dots, while on the other half, the background together with the two lines (now identical in length) formed the well-known Ponzo and Müller-Lyer illusions through the Gestalt principle of grouping by similarity. Participants reliably responded in a manner consistent with the illusions (i.e. reporting that the appropriate line was longer), even though the vast majority of them were not aware of seeing the background pattern. What is crucial here is that processing the background pattern is necessary for the illusion to influence participants' responses. The conclusion is that participants perceived the right background grouping even though they had no awareness of having done so.

Do the results of Moore and Egeth (1997) establish that perceptual organization does not require attention? Not necessarily. Moore and Egeth (1997) had each participant view the displays with the illusions 16 times while they performed the line-comparison task, whereas Mack et al. and Rock et al. tested their participants' awareness of the background patterns after only the first time each participant saw the pattern. It is possible that Moore and Egeth's participants learned implicitly and unconsciously that the background was informative and divided their attention between the primary and the secondary stimuli. Furthermore, they report that once the participants were aware of the Ponzo illusion, their performance of the line-judgment task dropped to chance levels, suggesting that the illusion was no longer effective (this pattern did not obtain with the Müller-Lyer illusion). Thus, for the Ponzo illusion at least, attention *does* play a role in perceptual organization.

Beyond Gestalt Grouping Principles

Taken together, the results from Mack et al. (1992), Moore and Egeth (1997) and Rock et al. (1992) suggest that attention can influence perceptual organization. Gestalt theory offers no way of accounting for this, as on this view perceptual grouping is largely determined by stimulus properties. Palmer (1999) and Pomeranz and Kubovy (1986) have pointed out further problems for the Gestalt view. First, the Gestalt principles don't distinguish between objects and groups of objects. Also, Gestalt principles ignore the role of top-down, general-purpose knowledge in perceptual organization. For instance, the Gestalt principles cannot explain why people who don't know that Figure 1 is

¹ I would like to thank the anonymous reviewer who brought this to my attention.

a picture of a Dalmatian usually fail to see any meaningful pattern in the image, whereas people who are aware that the image represents a dog not only find the dog easily but also organize the stimulus so that otherwise indistinguishable black dots become a dog, a sidewalk, and the shade beneath a tree.



Figure 1: Spot the Dalmatian!

In order to address these problems, an account of perceptual organization must do two things: it must show how perception and attention interact to form a-objects, and it must show how general-purpose conceptual knowledge can participate in the formation of a-objects without requiring full object recognition. Both of these objectives could be facilitated by construing perceptual organization as Inference to the Best Explanation (IBE), whereby where the visual system infers three-dimensional structures which best explain the retinal image (Hoffman, 1998; Leyton, 1992; Feldman, 1999)². IBE is an appealing account of human explanatory practice in general, but it suffers from the defect that explanatory ‘goodness’ has not yet been properly defined (Lipton, 1991). Nevertheless, vision researchers provide some candidates for goodness criteria in perceptual inference. Albert and Hoffman (1995), Feldman (1999), and Pomerantz and Kubovy (1986) have suggested that visual inference is overarchingly guided by the principle of genericity. That is, the visual system assumes, in the absence of other data, that the retinal image is a generic view of three-dimensional objects, rather than a very specific and “accidental” view of some other set of three-dimensional objects. A generic view is a two-dimensional projection of a three-dimensional structure that does not entail special or accidental circumstances in the projection. For instance, a straight line in the retinal image is a generic view of a straight edge in the environment, but would be a non-generic view of a curved edge that just happens to be seen head-on. The genericity principle can account for a large number of phenomena of perceptual organization. Furthermore, Pomerantz and Kubovy (1986) show that the Gestalt principles can and should be reinterpreted as instances of the genericity principle.

The notion of genericity can be extended to explain the role of conceptual knowledge in perceptual organization. Assuming an observer expects to see a Dalmatian in Figure

1, the splotches obviously form a generic view of the dog. Whereas, if the splotches corresponded to a horse, it would have to be either a typical horse seen under very specific shading conditions, or a strangely Dalmatian-like horse seen under normal viewing conditions. “Explaining” the image as that of a horse would require invoking a number of special circumstances, which interpreting the image as that of a Dalmatian does not. The visual system might thus limit the conceptual information involved in constructing a-objects to knowledge of generic views and expectations about which objects are present in a scene.

A-objects can now be re-defined: An a-object is a representation of the three-dimensional structure that best explains the two-dimensional retinal stimulus according to the genericity principle, which takes into account both physical stimulus properties and general-purpose conceptual knowledge.

Although the Dalmatian example demonstrates the role of semantic information in perceptual organization, it remains to be shown that a-objects as defined above actually play a role in object-based attention. The following section presents some recent experimental evidence bearing on this issue from our laboratory.

Recent Evidence for the Involvement of Attention in Perceptual Organization

A first line of evidence for the role of attention in perceptual organization comes from recent studies on object-based attention using moving stimuli (Jarmasz, 2001; Jarmasz, Herdman & Johannsdottir, in preparation). In these experiments, participants were shown a display consisting of two groups of identical dots. One set of dots was static, while the dots in the second group moved in unison in an elliptical trajectory that overlapped the location of the static dots. During each trial, two of the dots in the display changed color from light gray to one of two colors (either red and green, or blue and yellow). The target dots were located both in the static group, both in the moving group, or one in each group. Participants were required to determine whether the target dots were the same color. On some trials participants had to focus their attention on only one group of dots, while in other trials they had to spread their attention to the display as a whole, and avoid focusing on a specific group. When participants attended to the whole display, they responded significantly faster to target dots displayed within a single group than to targets appearing across both groups. The results were consistent with those found in the object-based attention literature using static displays (e.g. see Lavie & Driver, 1996; Treisman et al., 1983). However, when participants focused on only one of the groups, their responses were faster when both targets appeared in the attended group, and slowest when targets appeared either in the unattended group only or across groups. A comparison of response latencies across attentional focus conditions suggests that focused attention inhibits information processing of unattended stimuli rather than enhancing processing of attended stimuli relative to

²This does not necessarily imply deliberate, conscious inference.

situations where attention is deployed across the whole display. In all attentional focus conditions, both groups of dots overlapped in the display, so foveal limitation on visual acuity likely do not account for these results. Rather, they suggest that deliberate attentional allocation strategies influence the degree to which multiple perceptual groups are perceived as being separate from the others, or conversely as being part of a larger whole. This is consistent with the proposal above that a-objects depend on attentional factors as well as bottom-up stimuli properties.

A second line of evidence implicating attention in perceptual organization comes from a study using static visual objects (Jarmasz, 2002). In this study, participants were shown a display based on one used by Lavie and Driver (1996) consisting of two intersecting dashed lines. On each trial, two of dashes were replaced by two target elements, either a shorter dash or a gap (absence of a dash). The target elements could appear either near to each other on separate lines ('near' condition), far from each other on separate lines ('far' condition) or far from each other but on the same line ('object' condition). On half the trials, both dashed lines were the same color (either pink or yellow), whereas in the other trials each line was a different color. In all cases, participants responded most quickly to targets in the object condition, even though they were approximately seven times further apart in the object condition than in the near condition, thus replicating the effect found by Lavie and Driver (1996). When the dashed lines were of different colors, participants were equally slow in responding to targets in the near and far conditions relative to the object condition. However, when both lines shared a common color, participants responded more quickly to targets in the far condition than in the near condition (responses to targets in the object condition were still fastest overall). This suggests that in the same color condition, participants parsed the display either as two separate lines or as one large figure, depending on the location of the targets. These results further suggest that observers can implicitly acquire top-down attention allocation strategies that affect the perceptual organization of a stimulus from bottom-up cues (color & target location).

The two studies described above show that attention can be deployed, either implicitly or explicitly, so as to influence perceptual organization. The results of these two studies are inconsistent with the spotlight model of visual attention, in which spatial separation, but not shape, affects how quickly two stimuli are compared. However, the "standard" object-based attention model cannot account for these results either, as on this model perceptual grouping is assumed to be preattentive, and thus impervious to changes in attentional allocation strategies. An adequate account of visual attention and object perception will have to explain both how perceptual organization can affect attention (i.e. object-based attention) and how attention can affect perceptual organization. The next section presents such a model.

Towards a New Theory of Object-Based Attention

Current accounts of object-based attention do not reflect the reciprocal influences between attention and perceptual organization. Consequently, I propose a new account, the Inferential Attentional Allocation Model (IAAM; Jarmasz, 2001). Briefly, on this model attention and perceptual organization interact to incrementally build up representations of c-objects. Potential a-objects are constructed from regions of uniform color, luminance, and texture, and edge-bound surfaces in the visual stimulus (Palmer, 1999). These potential a-objects represent rival hypotheses as to the 3-D structures in the environment, and lack detail. A-objects are refined through cycles of grouping and selection (Grossberg, Mingolla & Ross, 1994). At each cycle, attention selects a-objects that best satisfy both genericity and cognitive set (i.e., an observer's perceptual expectations and general-purpose knowledge). This progressively liberates resources for generating more detailed a-objects that better "explain" the retinal image. If this process is interrupted before it culminates in stable a-objects, an observer may fail to perceive a c-object (Di Lollo, Enns, and Rensink, 2000, have found evidence for such a phenomenon). Figure 2 depicts these iterative processes.

The IAAM is a heuristic (i.e., exploratory) model. Even so, it allows for the following predictions: (1) stimulus-dependent, bottom-up information constrains possible a-objects in the scene, and as well as how much attentional resources the stabilization of particular a-objects will require; and (2) conceptual, top-down knowledge acts to determine which a-objects will eventually become stable and become p-objects. Thus, bottom-up properties of a stimulus should determine how "easy" it is to perceive certain objects, i.e., how much attention perceiving those objects will require and how efficient the processing will be. Top-down factors will sometimes push the visual system to organize a stimulus into more attentionally demanding configurations which will result in less efficient processing (reflected either in slower processing or more interference from other stimuli). The experiments reported above are largely consistent with these hypotheses. Common motion (a bottom-up factor) makes the segregation of a stimulus into distinct objects possible, but the intention to pick out one of these objects (top-down) enhances the processing of that object at the expense of processing information from other objects (Jarmasz, 2001; Jarmasz, Herdman & Johansdottir, in preparation). Similarly, collinearity and common color (bottom-up) facilitate the segregation of two dashed lines into two objects, but implicit task demands (top-down) seem to determine whether the two lines are actually parsed as one large figure or two lines (Jarmasz, 2002)

Further work is needed to elaborate and test the IAAM. Namely, the notions of 'ease' of perceptual grouping and of efficiency of visual processing need to be operationally defined. Nevertheless, one can imagine how the IAAM

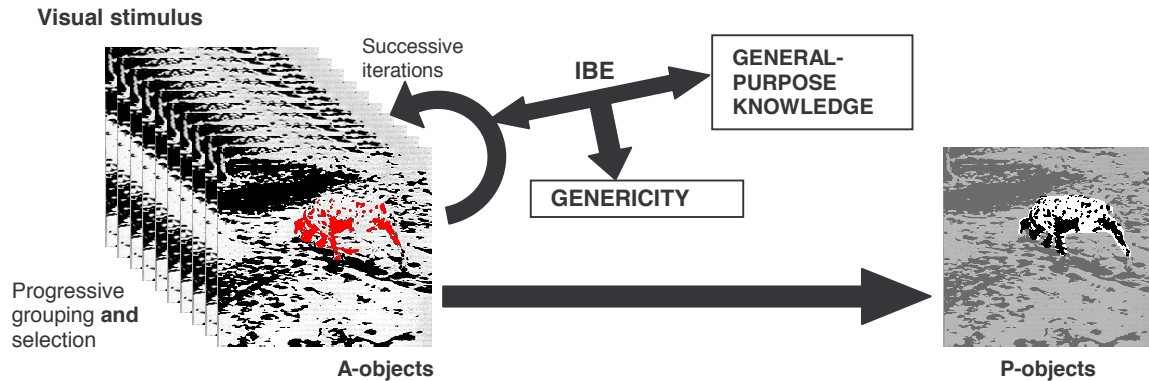


Figure 1: Grouping and selection processes in the IAAM

might apply to “real world” stimuli. For instance, if someone intends to move a box with a lid from a table to the top shelf of a bookcase, they will form a single a-object corresponding to the box and its lid. If, however, that person wants to open the box, they will form two a-objects, one for the lid and one for the box. On this view, a-objects are interest-relative; that is, a-objects depend on an observer’s goals and general-purpose conceptual knowledge, in addition to bottom-up stimuli. This is in contrast to the standard view, where a-objects are defined purely by stimulus properties.

Conclusion: Some Implications of the IAAM

The object-based model of attention is currently based on the assumption that visual attention selects perceptual groups that are formed preattentively according to the Gestalt grouping principles. This conceptualization of visual attention does not reflect the reciprocal influences between perceptual organization and attention, and further ignores the role of top-down information in perceptual organization. Moreover, this formulation is limited in its ability to guide human factors research, where broad principles are often lacking and problems often require ad-hoc solutions. A growing body of experimental evidence supports the notion that while attention is influenced by perceptual organization, it in turn influences whether and how perceptual organization occurs as well. Consequently, a new model of object-based attention, the Inferential Attentional Allocation Model, is proposed which attempts to capture the interaction between attention and perceptual organization. On this model, visual attention is object based not because attention selects objects, but rather because attention itself is indispensable to perceptual organization.

The IAAM is a heuristic model. In addition to providing a framework for developing a comprehensive account of visual attention, the IAAM also has potentially significant implications both for human factors research and for the metaphysics of concrete particulars. Regarding research on human factors, the IAAM shows that strategies for deploying attention interact both with visual stimuli and

with task demands. Thus, the design of graphical user interfaces such as desktop computer applications and head-up displays in aircraft and automobiles should take into account how a user’s cognitive and attentional sets might interact with the display.

The IAAM shows that what counts as an object for the visual system depends intimately on an observer’s goals and expectations. This reminds us that in a larger sense, everyday objects are embedded in a complex web of human activities and conventions. Standard metaphysical theories generally attempt to define concrete particulars without any reference to the agents that use and perceive them (e.g., see Loux, 1998). However, assuming that at least the broad lines of the IAAM are a valid account of object-based attention, what counts as an object for us as agents also depends on our expectations, intentions and general background knowledge. The criteria of “objecthood” might ultimately depend as much on epistemic issues as on metaphysical ones, as suggested by Smith (1996). Attention is object-based not only because attention and perceptual organization are mutually dependent, but also because objects would not be objects if we did not perceive them as such, but merely relatively coherent portions of the spatiotemporal flux we call the universe.

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