The ‘Deployment of Extra Processing’ Account of Attention

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Abstract

The paper formulates an alternative view about the core function of attention claiming that attention is not selection but the deployment of extra processing capacity. This way of thinking about attention has greater explanatory power, since it proposes a common implementation both for selection and modulatory effects, and it offers a unificatory perspective on the workings of perception and cognition.

Keywords: attention; selection; modulation; working memory

Introduction

In recent years, the theoretical and empirical literature on attention has gone through an exponential growth not just in sheer volume but also in diversity, which has lead many to claim that attention, after all, is not a unitary mechanism but rather a feature of “multiple perceptual and cognitive control mechanisms” (Chun, Golomb, & Turk-Browne, 2011, p. 74) operating at almost all stages of the perceptual-cognitive system. From this perspective, it becomes a crucial question whether there is a common core function of the different forms of attention.

Traditionally, the core function of attention is claimed to be selection: attention selects the relevant ones from the pool of concurrently present stimuli (Broadbent, 1958). This view goes back as far as William James’s account (James, 1890/1983), and is the ‘received view’ in contemporary literature (Petersen & Posner, 2012; Chun, Golomb, & Turk-Browne, 2011).

We call this view, according to which attention *is* a form of selection, the *Selection View* (SV). Our aim in this paper is to challenge this traditional understanding. In what follows we shall argue that both the selective aspect of attention, and its modulatory effects (Reynolds & Chelazzi, 2004) that are often claimed to realise the function of selection, are, in fact, implemented by the same mechanism, namely the *continuous and flexible re-allocation of processing resources*, and that the features of this mechanism are the common core characteristics of all forms of attention. We call our approach the *Deployment of Extra Processing View* (DEP). It is motivated by the ideas that have been implicit in much of the current research in vision science (Carrasco, 2011, 2014).

Attention as Selection

According to SV, the core function of attention is selection: it functions over information processing channels and decides which one of these can reach further processing. This view is in the centre of the early vs. late selection debate that dominated much of the research on attention in the 20th century. Early selectionists claim that basic physical features of all stimuli are detected and processed pre-attentively, and attention selects a few of these channels for categorical processing (Broadbent, 1958). Late selectionists claim that all stimuli are processed pre-attentively even to a categorical level, and attention makes a few of these channels available for post-perceptual (e.g. working memory) processing (Deutch & Deutch, 1963).

It needs to be acknowledged that SV is not a homogenous position—there are many varieties, even beyond the question of what point of perceptual processing attention (that is, selection) presents a bottleneck. Originally, SV pictured attention as a single mechanism dividing perceptual-cognitive processing into a pre- and a post-attentive stage. However, theorists nowadays argue that instead of one single or a few major stages of selection filtering effects occur throughout the processing stream (Driver, 2001). Accordingly, selection mechanisms operate at many different levels of the perceptual-cognitive system, making it, at least, *prima facie* unclear what attention is selection *for*. Some argue that attention selects for later stages of perceptual processing (Lavie, 1995), others claim that attention selects for working memory (Knudsen, 2007), still others talk about attention as selection for action (Allport, 1987).

These many possible stages or forms of selection are sometimes brought under the same umbrella by the general characterisation that attention is selection for *further* processing, where the processing in question takes place further up in the perceptual-cognitive hierarchy (Chun, Golomb, & Turk-Browne, 2011). However, what really serves as the common denominator of these very different versions of SV is that they all take attention to be a form of selection: what attention *is* is selection. Further processing of stimuli is an optional consequence that may or may not follow attention. That is, according to SV, attention, at any given level where it is in operation is, so to speak, a *gatekeeper*—a separate mechanism controlling the flow of information through the perceptual-cognitive system.

Attention as DEP

Thinking of attention as selection has been the mainstream view. But there is an alternative way of thinking about attention, one that is often implicit in works of vision scientists. It has long been known that the focus of spatial attention is able to enhance the processing of visual stimuli (Posner, 1980). For example, when attention is focused on a region of the visual field processing efficiency is increased compared to cases when attention is distributed over larger regions. In recent years, studying early vision, and utilising very simple displays, Marisa Carrasco and colleagues have shown that the increase in processing efficiency is due to attention's ability to affect very low level perceptual processing like spatial resolution (Yeshurun & Carrasco, 1998), contrast detection (Carrasco, Ling & Read, 2004) and even saturation detection (Fuller & Carrasco, 2006). According to these studies, attention *facilitates* these low level perceptual processes—it improves performance in several tasks by signal enhancement, i.e. by enhancing spatial resolution, and increasing (even apparent) contrast and saturation.

These studies suggest that attention is able to directly affect how much processing capacity is to be allocated to different stimuli (even right at the very entry level of the perceptual system). From this perspective, attention is not a gatekeeper but rather an *information processing booster* that is able to modulate perceptual processing by affecting the *allocation of processing resources*. This reinterpretation resonates quite well with how Marisa Carrasco herself summarises the moral of her research: "attention is involved in distributing resources across the visual field" (Carrasco, 2014, p. 184).

This is the way of thinking about attention that we call DEP. According to this alternative account, the core function of attention is the allocation of extra processing capacity: when one voluntarily attends to a specific spatial location or when a particular stimulus automatically captures one's attention what happens is that extra processing resources get allocated to the specific spatial location or particular stimulus. That is, attention increases the allocation of processing resources to the attended region or stimulus. It might be the case that a particular stimulus has already been processed before a novel engagement of attention, so a certain amount of processing capacity has already been allocated to it. However, when attention shifts to this stimulus *extra* resources get deployed facilitating the processing of the stimulus. Similarly, when one voluntarily withdraws one's attention from a specific region or when one's attention gets automatically disengaged from a particular stimulus the processing capacity allocated to the region or stimulus in question decreases. That is, according to DEP, the voluntary and automatic engagement and disengagement of attention *consist in* the active management of processing resources.

The Allocation of What Resources?

Before moving on, a clarification is in order. So far, we have been talking about the allocation of certain resources, but we haven't elucidated what resources we have in mind. Here we propose that processing resources are best to be understood as the natural processing capacity of the perceptual system, i.e. representational encoding via spike generation. Stimuli are processed through a hierarchy of neuronal circuits that encodes stimulus-features as specific firing patterns. Spike generation has a particular energy cost (Lennie, 2003), so ultimately, the resources in question are energy resources. By allocating more resources, attention improves the quality of the representations of the target features. Note that this is in line with how Carrasco thinks about the resources attention distributes. As she puts it: "attention augments perception by optimizing our representation of sensory input and by emphasizing relevant details" (Carrasco, 2014, p. 208).

Comparing Explanatory Power

One might wonder at this point whether the difference between SV and DEP is merely verbal. We believe that the two views are substantially different: they have different explanatory power (see this section), and integrative potential (see next section). On these grounds, we argue that DEP is preferable to SV.

Selection or Modulation?

As it has become increasingly evident in recent years, the modulatory effect of attention on neural activity is a general phenomenon. As it is sometimes put, nowadays it is "overwhelmingly apparent" that attention modulates neuronal responses across many stages of the perceptual-cognitive system (Squire, Noudoost, Schafer & Moore, 2013, p. 452; see also Reynolds & Chelazzi, 2004).

That is, the ability to modulate neural activity seems to be a key feature of attention—a mark of the operation of attention that, arguably, is just as widespread and fundamental as selection itself. It seems as though modulation was just as common and just as core a function of the many different forms of attention as selection is often argued to be.

Note, however, that SV sees modulation and selection as two distinct features of attention that require two distinct independent explanations. As some of the proponents of SV explicitly acknowledge (Chun, Golomb, & Turk-Browne, 2011, p. 75), it is not a necessary feature of attention that a selected stimulus must be processed in an enhanced, or in an any way modulated manner. Following the gatekeeper analogy, it very well might be the case that attention selects certain information processing channels by simply blocking competing channels, without affecting in any way the working of the processing channel left intact. Consequently, for SV—that puts selection effects into the centre of thinking about attention—modulation requires additional explanation (Chun, Golomb, & Turk-Browne, 2011, p. 76).

Here we propose that DEP is preferable over SV because contrary to the latter the former is able to account for both selection and modulation on the basis of a single mechanism, namely the eponymous active management of processing resources.

As we have seen, DEP is motivated by the modulatory effects of attention, and therefore accounting for modulation within this framework is quite straightforward. If what attention is is the deployment of extra processing capacity, then the processing of attended information is enhanced, compared to the baseline level of processing preceding the allocation of attention. Similarly, if the disengagement of attention consists in a drop of the available processing capacity, then the processing of newly unattended information diminishes compared to the pre-disengagement level. That is, attention as the deployment of extra processing directly affects the neural activity relevant for the encoding of quality representations.

According to DEP, selection is also a consequence of the active management of processing resources. In fact, within this new framework there is a gradual shift between modulation and selection, with modulatory effects coming in various degrees and (full-blown) selection being at the far end of the same continuum.

Selection and DEP

It is a fundamental characteristic of attention that it is not possible to attend to too many things at once or to distribute attention over a large region of the visual field without a decrement in processing efficiency. That is, selection seems to be inevitable. And indeed, given our understanding of processing resources, selection is a consequence of the allocation of processing capacity, since energy resources required for spike generation and representational encoding are very limited. Lennie (2003) argues that the cost of spikes in the brain is high compared to the known energy consumption of the cortex, which severely constrains the activity that can occur concurrently. Lennie concludes that due to this limit in the energy resources available, the energy resources need to be flexibly re-allocated again and again in accordance with actual task demand.

So when the capacity limit is reached and all the resources are allocated then any novel act of voluntarily attending or episode of automatic attentional capture must necessarily co-occur with a withdrawal of some processing capacity from unattended regions. That is, the active management of processing resources, when operating near limit, consists in the joint allocation and withdrawal of resources: shifting attention is shifting the allocation of (i.e. re-allocating) processing capacity. Allocating extra resources to a particular stimulus decreases the amount of processing capacity that can be deployed elsewhere—this is how the particular stimulus in question gets selected and why unattended stimuli ‘fade away’.

Note that although in the case of near-limit operation all novel instances of allocating extra processing resources to certain stimuli co-occur with the withdrawal of some processing capacity from other stimuli, this does not necessarily mean the full withdrawal of attention from unattended stimuli (i.e. full-blown selection). There very well might be cases where only part of the processing capacity already allocated to some stimuli gets withdrawn with a novel engagement of attention at another location. In these cases some (residual or excess) processing resources remain allocated to the original (now unattended) stimuli due to which these stimuli are still processed to a certain degree. These are the cases of partial or distributed attention (Cohen, Cavanagh. Chun & Nakayama, 2012) with incomplete or inefficient attentional selection (Benoni & Tsal, 2013).

Full-blown selection (i.e. the total blocking of the processing of unattended stimuli) only happens if all processing resources are consumed by a single stimulus (or a single set of stimuli—the attended one) and thus no processing capacity could be allocated to other stimuli.

Is Selection Necessary?

According to DEP, thus, the core function of attention is the amplification of representational encoding of salient or task relevant stimuli via the allocation of extra processing resources. Selection effects are only by-products of this amplification and especially the corresponding attenuation of the representational encoding of inconspicuous or irrelevant stimuli that results from the fact that processing resources are of limited capacity.

Note that according this view, selection is far from being *the* core function of attention—it is not even a necessary consequence of the mechanisms underlying the allocation of attention. In systems without resource-limits, or (more realistically) in systems operating far from their limits, there can be spare capacity at the system’s disposal to be allocated to new stimuli. In these cases, though attention—as the deployment of extra processing resources—is very much in operation, no selection effects occur, since no processing capacity needs to be withdrawn from unattended stimuli.

This way of thinking about selection, however, might be called into doubt by the very low level studies that have originally motivated DEP. In a series of studies, Carrasco and colleagues show that even in the case of very simple, non-cluttered displays with only two stimuli, when attention facilitates contrast sensitivity and acuity at the attended location, trade-offs (*decreased* contrast sensitivity and acuity—compared to the baseline) appear at the non-attended location (Pestilli & Carrasco, 2005).

On the face of it, this finding is in tension with the idea that selection effects occur only when the system operates near limit (i.e. when perceptual resources are fully allocated). The problem is this: in the experimental paradigms used in the studies above, the displays, typically containing only two Gabor-patches, are so simple that their capacity requirement in the baseline condition could hardly exceed, or even get close to, the capacity limit. So when one attends to the location of one of the stimuli extra processing capacity could very well be deployed without the necessary withdrawal of processing resources from other locations. That is, this finding seems to show that selection effects can occur even if the full processing capacity is only partly allocated.

We, however, think that these results are, in fact, perfectly compatible with DEP. What they suggest, is that the *limited processing capacity* (at least of early visual processing, see below) *is always fully allocated*. That is, we interpret the Carrasco studies in question as indicators that early visual processing always operates near limit. The low levels of the visual processing stream seem to be unable to reserve spare (unallocated) processing capacity that could be deployed without any occurrent cost. Therefore, processing capacity is fully allocated even when subjects are faced with the simple displays in the Carrasco studies. When attention is captured at a certain location overlapping with one of the stimuli, and extra resources get allocated to the processing of this stimulus, then resources from other locations must be withdrawn.

The claim that the limited processing capacity of low level visual perception is always fully allocated finds plenty of support in the literature. For example, Treisman (1969) suggests that “we tend to use our perceptual capacity to the full on whatever sense data reach the receptors” (Treisman, 1969, p. 296). The idea here might be that active inhibition is unavailable for low level perception, so “the nervous system is forced to use whatever discriminative system it has available, unless these are already fully occupied with other tests or inputs” (Lavie, 1995, pp. 452-453). Indirect evidence might further be provided by Lennie (2003) who claims that the sensory cortex is “among the most active metabolically” (Lennie, 2003, p. 496), i.e. it seems to be much more active than other parts of the cortex with comparable number of neurons. A possible source of further support might be the observation that even in no stimulus conditions the spontaneous activity of the primary visual cortex is very strong and coordinated, resembling stimulus (natural scene) evoked activity (Berkes, Orbán, Lengyel, & Fiser, 2011).

To sum up, selection effects do not necessarily follow from the deployment of extra processing, but whenever a (sub-)system operates near its capacity limit selection effects will always occur. As the Carrasco studies, energy considerations, or observations related to spontaneous activity suggest, early vision might very well be such a sub-system. If so, then shifts in attention are always accompanied by the re-distribution of the limited processing capacity of low level visual perception—it will be fully allocated all the time, but slightly differently: the actually attended location will receive more resources, the actually unattended locations will receive less resources.

Finally, note that this picture is compatible with the active inhibition of unattended stimuli (Cerf, Thiruvengadam, Mormann, Kraskov, Quiroga, Koch, & Fried, 2010), since active inhibition is, in fact, a tool for resource withdrawal.

DEP, Modulation, and Selection: an Overview

According to DEP, attention is the deployment of extra processing capacity. Since the processing capacity in question is, in fact, the set of available energy resources required for spike generation, the deployment of extra processing capacity results in enhanced representational encoding. Enhanced representational encoding is a form of modulation, so modulatory effects straightforwardly follow from the deployment of extra processing capacity.

If the system operates near limit (i.e. if the resources are always fully allocated), then the deployment of extra processing capacity will lead to the withdrawal of processing capacity from unattended stimuli (via, say, active inhibition). The withdrawal of some processing capacity from unattended stimuli decreases the quality of the representational encoding of these stimuli. Diminished representational encoding of unattended stimuli is equally a form of modulation, but it is also a form of selection: it is what is called partial (or incomplete, or inefficient) selection.

Finally, if the attended stimulus consumes all processing capacity then there is no residual capacity that could spill out to unattended stimuli, so unattended stimuli are not processed at all. They are stopped being representationally encoded. This is the case of full-blown selection.

In other words, if we accept DEP and the further assumption about the near-limit operation of at least certain perceptual sub-systems, then we become able to explain both the modulatory effects and the selective nature of attention. Therefore, since SV fails to explain why attention entails the modulation of signal processing, DEP is preferable because of its greater explanatory scope.

Perception and Cognition in the Light of DEP

In this section, we would like to point out that attention, as defined by DEP, is a natural ally of modern approaches to higher cognitive processes, especially the functioning of working memory. Working memory is generally thought of as the site where information conveyed by the senses and processed by the perceptual system is brought together and gets evaluated in accordance with the needs of ongoing tasks (Baddeley, 2003). Within this context, attention is often seen as the gateway to this site—as the set of mechanisms responsible for selecting which bits of information can gain access to working memory (Knudsen, 2007). Moreover, it has recently been argued that there is a significant overlap between attentional and working memory functions (Awh, Vogel & Oh, 2006; Gazzaley & Nobre, 2012). In the light of these results, it is timely to reconsider whether the way we think about attention matches our most up-to-date accounts of working memory.

Slot vs. Resource Models of Working Memory

Perhaps the most characteristic feature of working memory functions is that they are of limited capacity. In recent years, the nature of this limited capacity has hotly been debated (Luck & Vogel, 2013; Ma, Husain & Bays, 2014).

Classically, the limited capacity of working memory is interpreted as a limit in the number of discrete representations that can actively be maintained to serve the needs of ongoing tasks. The observations according to which working memory is able to hold only 3-7 items at once (Cowan, 2001) is typically modelled by a slot-based account: working memory has a fixed number of slots that can store object or feature representations such that when an object representation gets into a slot the object will be remembered, and when it does not the object will not be remembered at all (Luck & Vogel, 2013). That is, if the number of items in the input is greater than the fixed number of slots then no information will be stored in working memory about the items that do not get into one of the slots.

Contrary to this, resource models conceptualise working memory as a limited resource that can flexibly be distributed between all the items in the input (Bays & Husain, 2008). The more resource is allocated to a particular item, the better the quality of the working memory representation of the item will be. That is, resource models shift the emphasis from the number of items that can be stored in working memory to the quality or precision of the memory trace of the items in question. The flexibility of resource allocation makes it possible to store enhanced quality representations of prioritised items while maintaining low quality representations of other items (Bays & Husain, 2008; Ma, Husain & Bays, 2014).

Attention and Working Memory

Note that SV with its item-based attentional shifts is a quite good match for classical slot-based accounts of working memory. Attention, according to SV, operates over information processing channels that process characteristics of individual physical features or objects. In this context, selecting a channel and blocking others amounts to passing on information about certain features or objects while filtering out others—providing ideal input for the fixed slots of working memory. The feature or object the information of which can get through the bottleneck will be represented in working memory, whereas those that are screened off will not be remembered. Similarly, shifting attention from one feature to another means that the filtering mechanism gets repositioned to the corresponding information processing channel passing on information about a new feature and blocking others—providing just the right sort of input to fill up another slot of working memory. That is, slot-based accounts of working memory and attention as defined within SV are natural allies. Attention as it is jumping in shifts from one feature or object to another delivers exactly that kind of information that is going to end up in working memory. Slots store what attention selects.

Resource models of working memory break with the notion of all-or-nothing representational encoding. They claim that working memory can and often does maintain partial (low quality) information about items that are not necessarily given priority in accordance with actual task demand. Note that by making this claim, and especially by anchoring the notion of the limit of working memory to resources required for creating quality representations, resource models of working memory commit themselves to the very same principles that underly DEP. Also note that the emphasis of DEP on the continuous and flexible re-allocation of these resources is also shared by the resource models of working memory. In fact, it seems that the very mechanism that DEP points out as the implementation of all attentional effects, is also able to implement the functioning of the working memory as recent resource models describe it. Reported overlap between attentional and working memory functions (Awh, Vogel & Oh, 2006; Gazzaley & Nobre, 2012) thus might very well be due to a common mechanism responsible for the implementation of both sets of functions: as attention enhances the quality of representational encoding of certain features via the allocation of extra processing capacity, it becomes possible for working memory to maintain more detailed and less noisy representations of these features, which, then, results that they can be recalled with more precision.

That is, whereas SV complements slot-based accounts of working memory quite well, it doesn't really match modern resource models. However, DEP re-conceptualises attention in a way that makes it a perfect fit for this latter approach to working memory that has become increasingly dominant in recent years.

Attention, Perception, Cognition

Finally, let's step back and take a bird-eye-view of what has been argued for so far. Seeing the re-allocation of processing capacity as the fundamental mechanism implementing attentional effects re-defines the relationship between attention, perception, and cognition.

First, it is an essential feature of perceptual processing that its resources get continuously re-allocated. In the course of this re-allocation the processing of certain stimuli receive extra capacity making these stimuli the attended ones. Attention, thus, is not an extra mechanism working on top of perception (as the traditional SV claimed it to be), but rather an aspect or a result of how perception itself works.

That is, attentional effects are just aspects of the natural unfolding of how the perceptual system does what it does.

Second, recent approaches to working memory teach us that even higher cognitive functions share the common characteristic of flexibly allocating processing resources. It seems, thus, that the fundamental principles our proposal points out underlie a broad range of mental processes from attention through perception to cognition.

Acknowledgments

This work was supported by the FWO Postdoctoral Fellowship 12B3914N and the DFF - EU MCA - COFUND Mobilex grant 1321-00165 (PF), and the EU FP7 CIG grant PCIG09-GA-2011–293818 and the FWO Odysseus grant G.0020.12 (BN).

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