The limits of top-down control of visual attention

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ABSTRACT

The extent to which spatial selection is driven by the goals of the observer and by the properties of the environment is one of the major issues in the field of visual attention. Here we review recent experimental evidence from behavioral and eye movement studies suggesting that top-down control has temporal and spatial limits. More specifically, we argue that the first feedforward sweep of information is bottom-up, and that top-down control can influence selection only after the sweep is completed. In addition, top-down control can limit spatial selection through adjusting the size of attentional window, an area of visual space which receives priority in information sampling. Finally, we discuss the evidence found using brain imaging techniques for top-down control in an attempt to reconcile it with behavioral findings. We conclude by discussing theoretical implications of these results for the current models of visual selection.

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1. Introduction

Our visual environment presents us with a variety of distractions that could interfere with even the simplest task, such as crossing the street or reading a book. To keep performance on track, information relevant to observers' goals and intentions needs to be selected, while irrelevant information needs to be filtered out. Spatial selection is said to be under top-down control when information is selected according to goals, intentions and beliefs of the observer, while selection is said to be stimulus-driven, or under bottom-up control, when attention is controlled by the physical properties of the scene irrespective of the observers' goals or intentions.

The extent to which we have control over what gets selected is a major question in vision research. Some theories postulate a dominant role for top-down control (Bacon & Egeth, 1994; Folk, Remington, & Johnston, 1992), while others stress bottom-up control (Itti & Koch, 2000, 2001; Nothdurft, 2000; Sagi & Julesz, 1985; The-

euwes, 1991, 1992, 1994, 1996, 2004), or a combination of both (Wolfe, 1994, 1998; Wolfe, Cave, & Franzel, 1989).

Recent studies on attentional control using different research methods (behavioral studies, eye movements and neuroimaging) have exposed the limitations of the contemporary theories and models of visual selection. The purpose of the present review is to discuss these findings in an attempt to integrate them into a coherent answer to the question of when, how, and to what extent spatial visual selection is controlled by top-down and bottom-up factors. We will argue that during the initial sweep of information processing visual selection is driven solely by bottom-up processes. The dominance of bottom-up control subsides with time, but whether this is due to the growing influence of top-down modulation, to passive fading of bottom-up information over time, or to a combination of both, remains an open question. In addition, we discuss recent evidence that top-down modulation has an effect on the size of the "attentional window" set up before the appearance of the display (Gibson & Peterson, 2001; Nakayama & Joseph, 1998). We will propose that salience computations are largely restricted to the attentional window, and that within the window no top-down control is possible. Taken together, the recent findings described in this review suggest that contemporary models of visual attention (Bundesen, 1990, 1998; Bundesen, Habekost,

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& Kyllingsbaek, 2005; Itti, 2006; Li, 1999; Treisman & Gelade, 1980; Wolfe, 1994; Wolfe et al., 1989) need updating.

We begin by describing current models of visual attention and their implications for control over visual selection. In the following sections, we discuss behavioral, eye movement and neuroimaging data challenging these models. In the section devoted to visual search the limits of top-down knowledge on search performance are discussed. The attentional capture section presents evidence suggesting that strong bottom-up signals cannot be overridden by top-down settings. The section on the eye movement control provides information about the relative time-course of top-down and bottom-up control. The last two sections discuss insights gained from brain imaging techniques (ERP and fMRI). We conclude by proposing a view on visual selection that integrates these recent findings.

2. What do the theories say?

Most current accounts of visual perception suggest that there are two main stages of visual information processing: a low-level preattentive stage and high-level attentive stage (Bundesen, 1990, 1998; Treisman & Gelade, 1980; Wolfe, 1994; but see Duncan and Humphreys (1989)). Preattentive processing occurs prior to the allocation of focal attention, has a large capacity and occurs in parallel fashion across the whole visual field. Attentive processing, however, has a small capacity and occurs only for a part of the visual field. It has been suggested that one of the outcomes of preattentive processing is a salience map: a map of locations with activation at each location indexing the relative salience of the (part of the) object at that location (Treisman & Gelade, 1980). The location with the highest activation (or, probabilistically, one of the highest activations) is then selected for further "attentive" processing. The question of top-down versus bottom-up determination of selection can be restated in terms of preattentive and attentive processing: do top-down factors influence preattentive processing? If the answer is "yes", top-down factors partly drive visual selection. If the answer is "no", visual selection would be based solely on bottom-up, stimulus-derived factors.

The most important bottom-up factor is local feature contrast. If an element differs in one or more features from the surrounding elements, its bottom-up salience is high (for a review, see Fecteau and Munoz (2006), Treue (2003)). If an element is surrounded by elements that have similar features, its bottom-up salience is low. Salience thus refers to the physical, bottom-up distinctiveness of an object (Fecteau & Munoz, 2006). Attentional selection driven by such bottom-up salience would be rather blind in many situations. If the target does not have unique features that make it salient, selection would be down to random sampling. An influential theory of visual attentional selection, Feature Integration Theory (FIT; Treisman & Gelade, 1980), made exactly this prediction. If selection could not be made on the basis of bottom-up salience, search would be random. This prediction proved to be wrong (see next section). For this and other reasons, most formal models of attentional selection following FIT have assumed that top-down factors partly determine the activations in the salience map (see Fig. 1). In Guided Search (Wolfe, 1994; Wolfe et al., 1989), activations in the salience map are a function of two factors: local feature contrast (bottom-up salience) and feature weights, which are determined by the search goals (e.g., white objects will have a high salience, thanks to a high "whiteness" weight, if the subject searches for a white target). In the Theory of Visual Attention (TVA, Bundesen, 1990, 1998; Bundesen et al., 2005), the probability of selection, modeled as the likelihood that an object feature enters short-term memory, is determined by the top-down feature weights set by the task (so-called *pertinence* values). Bottom-up
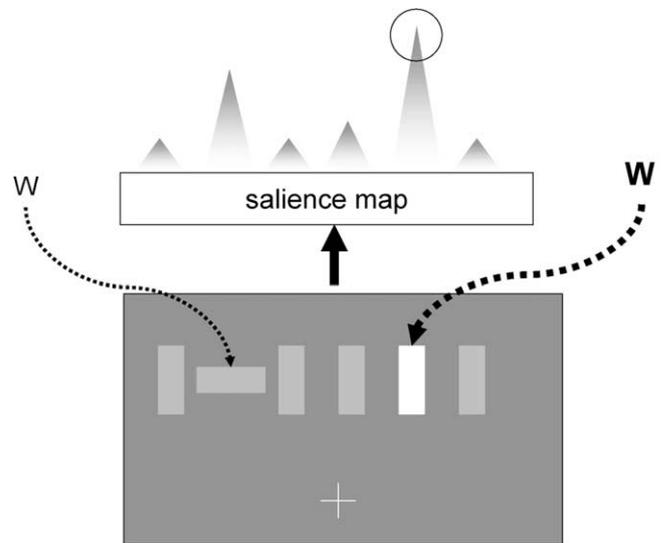
Fig. 1. Bottom-up and top-down determinations of salience (Guided Search). Salience is determined by local feature contrast, making the two distinctive elements in the display (here a horizontally-oriented bar and a white bar) high in salience as compared to the other bars. In addition, salience is determined by top-down weights for different features, such as a horizontal orientation or whiteness. Here, the top-down weight of whiteness is high relative to that of the horizontal orientation (size of the 'W'), making the white bar the most salient element in the display.

salience only plays an indirect role, in that items that share the same features are grouped and therefore lose individual salience.

There have also been pure salience-based models of selection (Itti, 2006; Li, 1999). The authors of these models acknowledge, however, that top-down factors influence attentional selection, and that purely bottom-up models are therefore a "coarse approximation" of human attention (Itti, 2006, p. 962), or represent an "idealization when top-down influences are not effective" (Li & Snowden, 2006, p. 912).

Models of visual selection usually do not explicitly model the effect of time or space on selection (Bundesen, 1990, 1998; Bundesen et al., 2005; Itti, 2006; Li, 1999; Treisman & Gelade, 1980; Wolfe, 1994; Wolfe et al., 1989). For a given visual display the models compute a salience map, and the highest value on this map is the predicted location to which attention is deployed. Theoretically, it is possible that early in processing, salience is computed from bottom-up factors alone, while top-down factors contribute late in processing (Theeuwes, 1991, 1992, 1994, 2004; Theeuwes, Atchley, & Kramer, 2000; Theeuwes & Godijn 2001; Theeuwes, Kramer, Hahn, & Irwin, 1998; Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999).

The idea of early versus late processing fits with earlier distinctions made by others (Bar et al., 2006; Hochstein & Ahissar, 2002; Lamme & Roelfsema, 2000; VanRullen, 2007). For example, Lamme and Roelfsema (2000) distinguished a feedforward sweep of initial activity from later recurrent processing in discussing processing of visual signals in the brain. In the feedforward sweep, neural activity generated by the visual display sweeps from low-level visual areas up to temporal, parietal and frontal areas in a feedforward manner. In subsequent recurrent processing, the higher-order areas influence firing in lower visual areas through feedback connections. In terms of early versus late processing, this might imply that when an attentional selection is made while the feedforward sweep still dominates processing it is by necessity made on the basis of purely bottom-up salience. Top-down influences bias attentional selection only after recurrent processing has already started. Such a link of source of control to time is also made in

models of the eye movement system (Kopecz, 1995; Meeter, Van der Stigchel, & Theeuwes, submitted for publication; Trappenberg, Dorris, Munoz, & Klein, 2001, see also Eye Movement section below). In these models, a distinction is made between a bottom-up signal that reflects visual salience, and a later top-down signal that boosts activity at the location of task-relevant stimuli (Kopecz, 1995; Meeter et al., submitted for publication; Trappenberg et al., 2001) or inhibits processing for task-irrelevant processing (Meeter et al., submitted for publication; Wijnen & Ridderinkhof, 2007). Eye movements made with a short latency are proposed to be made solely on the basis of the bottom-up signal, while slower eye movements would reflect a mixture of both bottom-up and top-down factors. The same might be true for visual selection in general.

What would count as the evidence consistent with such a link – i.e., of early selection being based on bottom-up factors, and later selection on the combination of top-down and bottom-up factors? One can derive two predictions from this conjecture. First, differences should be noticeable between conditions or trials in which selection is made early in time, and conditions or trials in which selection is made relatively late in time. When selection is made early in time (i.e., shortly following display onset), it should be driven by bottom-up salience only. When selection is made late in time, then top-down, task-related factors should influence selection. This prediction has been tested in various paradigms, which will be discussed in the following sections. A second prediction relates to brain activity. If top-down factors indeed do not influence early selection, these top-down factors should not affect brain activity in visual processing areas before the display is presented, or during initial processing of the display, i.e., the bottom-up sweep. We will review studies that have tested this prediction in later sections.

Another way in which the issue of top-down versus bottom-up control of selection could be resolved involves not time but space. Implicit in the idea of spatial attention is that some contiguous area in the visual field is selected, which receives priority in information sampling. This area has been referred to as the "attentional window" of observers (Nakayama, 1990), a concept similar to the "spotlight" (Posner & Petersen, 1990) or "zoom-lens" (Eriksen & St James, 1986). Although spatial attention is mostly investigated in the context of selection of stimuli once they appear, observers probably use their expectations to limit spatial selection in advance of stimulus presentation. One way in which top-down settings might influence performance is that observers adjust the size of the attentional window according to their expectations of the task. In particular, when observers expect an easy search, they presumably set their window so that it encompasses the entire display, and then pick the most salient element in it (Nakayama, 1990; Nakayama & Joseph, 1998). In case of a serial search task the window does not encompass the whole display. Instead, search elements are examined individually or in small clusters. If selection is limited to stimuli within the attentional window, setting the window size may provide a way for top-down control to influence selection from the first sweep on. This idea has been particularly useful in reconciling conflicting findings in the literature on attentional capture.

3. Top-down influences in visual search

Visual search refers to a class of paradigms in which participants have to find one element, the target, which is presented in a display together with irrelevant elements, the distractors. A distinction that is often made is that between *feature search* and *conjunction search* (Treisman & Gelade, 1980). In feature search the target has a feature that is not shared by any of the distractors, for example, in a search for a red target among green distractors.

In conjunction search, the target does not have a unique feature; instead, the target is defined by a conjunction of features, as for example, when a red T has to be found among red L's and green T's – here only the conjunction "red + T" defines the target and not the features individually. Feature search typically results in parallel search, meaning that the reaction times are largely independent of the number of elements in the display, while conjunction search requires serial search, in which the reaction times increase linearly as the function of the number of elements in the display (also referred to as efficient search and non-efficient search, e.g., Wolfe, 1998).

3.1. Conjunction search

Conjunction search was one of the first paradigms to show clearly that top-down factors can influence attentional selection. Egeth, Virzi, and Garbart (1984) had participants search for a red O between black O's and red N's, a typical conjunction search. They found that RT increased with increasing numbers of red elements in the display, as is standard in conjunction search. RT did not increase at all, however, when the number of black O's increased. Participants seemed able to ignore all black elements in the display, and restrict their search to the red ones. Kaptein, Theeuwes, and van der Heijden (1995) replicated this finding in ways that eliminated many confounds and alternative explanations, and Belopolsky, Theeuwes, and Kramer (2005) demonstrated that participants could search a group of briefly flashed elements, ignoring non-flashed elements. These experiments suggest that attentional selection is not blind, but can be influenced by top-down settings (e.g., to select only elements in the relevant dimension). Therefore, visual search is not random when selection cannot be made on the basis of bottom-up salience as predicted by the Feature Integration Theory (Treisman & Gelade, 1980).

Ignoring items with certain features is just one of many findings suggesting a role for top-down factors in visual search and thus, by inference in attentional selection. In fact, there is no clear dichotomy between parallel search and serial search (Wolfe, 1998). It has even been shown that conjunction search can be parallel (Nakayama & Silverman, 1986; Theeuwes & Kooi, 1994; Watson & Humphreys, 1997; Wolfe et al., 1989) and influenced by bottom-up processes (Geyer, Müller, & Krummenacher, 2006; Kristjánsson, Wang, & Nakayama, 2002). This suggests that a mixture of bottom-up and top-down processes is likely at play during conjunction search. The search slopes thus reflect how efficiently target features guide attention to the target, while participants also use the target feature information to form an attentional set to guide search in a top-down fashion (Bundesen, 1990, 1998; Bundesen et al., 2005; Duncan, 1989; Wolfe, 1994; Wolfe et al., 1989).

Due to this combined influence of bottom-up and top-down factors on conjunction search, conjunction search does not seem well-suited to test whether the first feedforward sweep of visual activity can be modulated in a top-down way. In addition, conjunction search is often quite slow which makes it unlikely that the responses are made solely on the basis of the first feedforward sweep.

3.2. Feature search

Evidence for top-down guidance of attention thus comes from studies in which search is slow. Is top-down guidance of attention also possible in fast and efficient search in which at least a subset of responses is based on the feedforward sweep of activity?

One piece of evidence in favor of top-down control comes from experiments in which the target feature was varied. If responses are based solely on bottom-up salience (i.e., feature contrast), it should not matter whether that feature remains constant over tri-

als. This prediction is not confirmed by the data. Treisman (1988) had participants search for a target among short black vertical lines. The target had either a different orientation, a different color, or a different size than the distractors. If the visual dimension of the target differed from distractors (i.e., orientation, color, or size) and remained constant over a block of trials, subjects were faster than when the three kinds of targets were randomly mixed within blocks.

Müller, Heller, and Ziegler (1995) extended these findings, and explained them in terms of top-down control of preattentive signals. Their explanation was couched in the framework of Guided Search (see Fig. 1). Feature maps that code feature contrasts are integrated into a master salience map, but Müller et al. (1995) suggested that these maps do not have to contribute equally to the salience map in all situations. Participants can give greater weight to the contribution of feature maps belonging to one dimension than to those belonging to another dimension. If, for example, they know that the target will have a different color than the distractors, color feature maps will be given a higher weight and will contribute strongly to activation in the salience map, whereas other dimensions, such as orientation or size will receive smaller weights.

In this view, the costs of varying features are created because participants cannot weigh the different dimensions when they do not know what will differentiate the target from distractors. In this so-called *dimension weighting account* the emphasis is thus on the knowledge of the participant of the target-defining dimension, both explicit (Müller et al., 1995) and implicit (Müller, Krummenacher, & Heller, 2004). The participant *knows* what he or she is looking for, this biases dimensional weights, which in turn makes search more efficient. Later findings suggested that such putative dimensional weighting was at least partially automatic. Müller, Reimann, and Krummenacher (2003) let participants search for targets that differed from distractors either in color or in orientation, randomly intermixed. Before each trial, participants received a verbal cue that informed them what dimension the coming target would pop out on. In addition, the authors looked at intertrial transitions: given that on trial $n - 1$ participants searched for a color target, would they be faster on trial n when the target dimension remained the same as opposed to when it changed? Müller et al. (2003) found an effect of both factors. Participants were approximately 20 ms faster if they were told what the target dimension would be (verbal cue effects), and were an additional 20 ms faster if the target dimension remained the same on two consecutive trials (intertrial effects).

Müller and colleagues (2003) explained intertrial effects by suggesting that participants are assumed to change dimension weights to optimize search for the current target, and that these changes carry over to the next trial. The intertrial effects are just one example of the *priming effects* that are ubiquitous in visual search (e.g., Maljkovic & Nakayama, 1994, 2000; Meeter & Olivers, 2006; Olivers & Meeter, 2006). Participants are faster if they have to search repeatedly for the same target. This is highly automatic, in that it occurs even when it is counterproductive. Theeuwes, Reimann, and Mortier (2006) let participants search for target singletons that differed either in shape or in color from the distractors. Before each trial, they cued participants by an example of one of the two possible targets. Theeuwes et al. made the cue counterpredictive: a cue indicated with a high probability that the other dimension (color or shape) would be the target on the next trial. For example, in one of the experiments the cue predicted with 83% validity that the other shape would be the target on the next trial. Nevertheless responses were faster in the 17% of trials in which a cue was followed by itself as the target. This suggests that the cue led to bottom-up, automatic priming which appears to be difficult to counteract by volitional top-down control (also see Meeter and

Olivers (2006), Theeuwes and Van der Burg (2007)). Such priming, including what was reported by Müller et al., cannot be used as a convincing argument for top-down attentional guidance in feature search.

The use of cues consisting of verbal labels (e.g., search for "red") is typically assumed to address top-down volitional control since it presumes that subjects get ready for the upcoming trial by preparing for the cued dimension (e.g., prepare for red). Several studies have shown cueing effects when employing these verbal cues (Meeter & Theeuwes, 2005; Mortier, Theeuwes, & Starreveld, 2005). However, in retrospect one may question whether these cueing effects truly support the notion of top-down guidance of attention in feature search. If cueing the dimension of the target ("It's going to be a color target!") affects attentional selection, then each task in which attention has to select the target should be speeded up by the verbal cues. To test this prediction Theeuwes et al. (2006) used verbal cues in two tasks: a present/absent task as used by Müller et al., and a *compound* search task. In compound search tasks, participants have to make a decision about the target element (e.g., whether it contains a vertical or horizontal line element). Müller and colleagues (2003) found clear effects of cueing the target dimension in the traditional present/absent search, but no effect in the compound search. Moreover, Mortier et al. (2005) found cueing effects even in a task in which there was no visual search. They presented participants with one central element. Participants had to respond if this element was a target defined by either form or color. In this situation, verbally cueing the dimension of the target still resulted in benefits relative to a neutral cue.

Informing participants about the upcoming target thus does not always aid them when visual search is needed (e.g., in compound search; Theeuwes et al., 2006), but does aid responding when search is not needed (Mortier et al., 2005). This suggests that cueing the target dimension does not speed up the search process or attentional deployment, but instead influences some other process. Indeed, several researchers have proposed that cueing of the target dimension affects only the response selection stage (see for a full account, Cohen & Magen, 1999; Mortier et al., 2005).

In summary, if top-down modulation of selection on the basis of the feedforward sweep exists, such modulation should be present for efficient, fast search. Participants are indeed faster when they have to search subsequently for the same target twice, but this benefit seems to be independent of the goals of the participants, and thus it likely reflects bottom-up priming and not top-down modulation. Participants are also faster when they are told what target to expect. However, this effect of top-down modulation seems to reside at the stage related to response selection and not at the stage of attentional selection. Taken together, these findings question the possibility of top-down control over the feedforward sweep.

4. Attentional capture

Another way to examine the extent of bottom-up and top-down control of visual selection is to pit them against each other in a single task. This is accomplished in the so-called *attentional capture* paradigms, in which the question is whether observers can ignore irrelevant bottom-up information. Attentional capture can be defined as an interruption of a goal-directed behavior by a strong "bottom-up" signal (e.g., an element with a salient unique color), which results in selection of a location, object or a motor program that is inconsistent with the top-down goals of observer. In order to de-convolve top-down and bottom-up control and to conclude that attentional capture by a certain feature has occurred, one has to make sure that the feature in question is irrelevant to the

task an individual is performing (Remington, Johnston, & Yantis, 1992; Theeuwes & Godijn, 2001; Yantis & Egeth, 1999).

The view that during *initial* visual processing control of visual selection is driven by the physical properties of the stimuli (Theeuwes, 1991, 1992, 1994) was based to a large extent on a series of studies using the "irrelevant singleton" paradigm. In these studies participants had to search for a unique object (with a unique shape, color or onset element) and respond to whether a line segment inside it was horizontal or vertical. In addition to the unique target object, a salient distractor object unique in a different dimension was presented on some trials. Note that in this task the bottom-up signal is clearly separate from the top-down goal: attending to the distractor would be a counterproductive strategy. Nevertheless, the presence of a salient distractor triggered a shift of attention to its location before attention was allocated to the target (Hickey, McDonald, & Theeuwes, 2006; Theeuwes, 1992, 1994, 1996). Therefore, a salient object in the visual field captured attention irrespective of the top-down goal. Importantly, the relative salience of the target and distractor objects was the critical factor (Theeuwes, 1992): when the target was more salient than the irrelevant singleton, attentional capture by the distractor was eliminated (Theeuwes, 1992, 1994).

The experiments described above can be interpreted with reference to a salience map. Both the target and distractor objects are represented on the map, with the distractor having a larger activation than the target. If activation in the salience map is determined by top-down goals, there should have been no interference from the distractor, but there is. The presence of a salient distractor slows down the search for the target (and it can also reduce the target's detectability, Theeuwes, Kramer, & Kingstone, 2004). To summarize, the discussed experiments suggest that attention is allocated according to salience and not according to the top-down goal, and thus that top-down control cannot be exerted over the initial parallel stage of visual processing.

According to another view (Jonides & Yantis, 1988; Yantis & Egeth, 1999), not all salient features are equally capable of attracting attention in a bottom-up fashion. Yantis and colleagues (Jonides & Yantis, 1988; Yantis & Egeth, 1999) used a visual search task in which the target of search was a non-singleton letter and in which the search was serial. On every trial one of the elements was salient on a particular dimension (color, brightness, motion, etc.): the target element was just as likely to be salient as any other element in the display. Therefore, there was no incentive to adopt a top-down strategy to search for a salient feature – it coincided with the target only on $1/N$ of all trials (where N is the number of elements in the display). The logic was simple: if the salient element captured attention then the search would always start at the salient element, and, if this was the target, no more elements would need to be searched. Jonides and Yantis (1988) showed that this was not the case. Search was approximately equally fast when the unique element happened to be the target as when it was not. They concluded that salient static singletons are treated in the same way as other non-salient elements in the visual field. Uniqueness in color or luminance was not sufficient to capture attention when it was irrelevant to the top-down goal (for a different conclusion using a "distance method" see Turatto and Galfano (2001)). Yantis and Hillstrom (1994) argued that only new objects have a special status in capturing attention irrespective of the top-down settings. This view was recently refined to include only luminance changes (Franconeri, Hollingworth, & Simons, 2005), and not the new objects per se. Nevertheless, the basic conclusion regarding salient static features remains the same: in a serial search task static features, such as color, shape, size or brightness do not capture attention.

A way to explain the discrepancy between these two views on attentional capture was suggested by Bacon and Egeth (1994).

They proposed that in the irrelevant singleton paradigm used by Theeuwes (1991, 1992) participants could have adopted a strategy in which they were looking for an item with a highest salience, a so-called "singleton-detection" search strategy. Since participants were intentionally searching for a singleton, an irrelevant distractor singleton in another dimension also captured attention. Capture was eliminated when the trials in which the target was not a singleton were mixed with singleton-target trials presumably forcing participants to search in a "feature-detection" mode, in which salience is not used but observers instead look for a particular feature. Leber and Egeth (2006) achieved a similar elimination of capture by training participants in a separate block of trials to engage in a feature search mode. However, in addition to eliminating capture, such training also resulted in elevated reaction times relative to a control group undergoing "singleton-detection" training. This suggests that "feature-detection" training led to a general slowing and, perhaps, more effortful but faster disengagement from the irrelevant distractor (Theeuwes et al., 2000).

Although the results of Bacon and Egeth (1994) and Leber and Egeth (2006) seem convincing, the idea that participants choose to engage into a search mode that hurts their performance seems implausible. In a recent study Theeuwes and Van der Burg (2008) investigated whether an instruction could force participants to engage into a feature search mode. Specifically, they examined the role of fore-knowledge of the target feature on attentional capture by a salient color distractor. Participants searched for an odd-one-out shape singleton (a diamond among circles or a circle among diamonds), and before each trial received either a word or a symbolic cue indicating the feature of the upcoming target. In either case, cueing reduced but did not abolish capture by a color singleton. Although this manipulation is arguably different from a feature search mode described by Bacon and Egeth (1994), the results suggest that getting ready to search for a certain target feature does not prevent attentional capture.

The notion of search modes is a part of the *contingent capture hypothesis* (Folk & Annett, 1994; Folk et al., 1992), which states that only the salient features that are relevant to the "attentional set" of the observer (i.e., whether the observer is looking for onsets, colors, etc.) capture attention. If there is no match, even salient objects, such as new objects, accompanied by a luminance increment ("onsets"), should fail to capture attention. In these experiments, observers were required to identify the unique element. There were two types of target display: In the *color* display the target was red while the other three elements were white. In the *onset* display, only one element was presented, and so the target was characterized as being the only element with an abrupt onset. Immediately preceding the target display at 150 ms SOA, a cue display was presented. Cue displays also were of two types: a cue defined by a color or by an onset. The cue that preceded the search display could be either valid (i.e., it appeared at the same location as the target), or invalid (i.e., it appeared at another location than the target). The critical finding of Folk et al.'s studies was that the cue only captured attention when it matched the target definition. Thus, when searching for a red target singleton, attention automatically shifted to the location of an irrelevant red cue, while an onset cue had no effect on performance. In contrast, when searching for an onset target a red cue had no effect, but attention automatically shifted to the location of an onset cue. This suggests that top-down attentional set determines the selection priority: when set for a particular feature singleton, one will select each element that matches this top-down set; feature singletons that do not match top-down attentional sets will not be selected and will simply be ignored.

Recently, Theeuwes (2004) suggested that the size of the *attentional window* of observers could be one of the factors explaining why salient color singletons fail to capture attention in some stud-

ies using a visual search task (Bacon & Egeth, 1994; Folk & Annett, 1994; Jonides & Yantis, 1988; Leber & Egeth, 2006). As discussed earlier, observers may adjust the size of the attentional window according to their expectation of a search task (see also Gibson and Peterson (2001), Nakayama and Joseph (1998)). In the case of a parallel search task, participants presumably set their window so that it encompasses the entire display, and pick the most salient element in it. In case of a serial search task the window does not encompass the whole display. Instead, search elements are examined individually or in small clusters. This increases the chance that the unique element is not included in the initial salience computations and does not capture attention. Changing the attentional window therefore changes the set of objects that are attended. Within the attentional window, no top-down control is possible and attention is first shifted to the location of the most salient feature.

In studies that did not find capture by a color singleton visual search often occurred in a serial or partly serial fashion, suggesting that participants adopted a small window (Jonides & Yantis, 1988; but see Leber and Egeth (2006), Yantis and Egeth (1999)). When the target is a unique object, as in the task used by Theeuwes (1992, 1994), the optimal strategy to find the target is to divide attention across the whole display (Nakayama & Joseph, 1998). As a consequence, the uniquely colored item that falls inside the attentional window is processed in parallel and captures attention. This idea is indirectly supported by the finding that when a target location is known in advance, even abrupt onsets do not capture attention (Theeuwes, 1991; Yantis & Jonides, 1990). Additional support comes from the finding that even feature search for a target with a unique orientation, which presumably does not require focal attention, is affected when participants have to detect a target in a centrally presented rapid serial visual presentation (RSVP) stream (Joseph, Chun, & Nakayama, 1997). This suggests that the mere focusing of attention in the center prevents salience computations across the visual field and disrupts efficient detection of a salient target in the periphery. In line with this, we claim that pigeonholing (i.e., selection of features; Broadbent, 1973) is only possible within the attentional window.

More direct evidence for the attentional window hypothesis was provided in a study by Theeuwes, Kramer, and Belopolsky (2004). These authors used a visual search task designed by Lavie and Cox (1997) to study the "perceptual load" hypothesis. According to this hypothesis the extent of processing of irrelevant information depends on the availability of attentional resources. If search is easy, as for example, searching for an X or N among only Os (low perceptual load), an irrelevant X distractor presented outside of the search display would result in a compatibility effect (i.e., a benefit when the target letter matched the distractor and a cost when it did not match the target). However, if the search task was difficult, as searching for an X or N among other letter distractors (i.e., not only Os but also Ps, Qs and Rs; high perceptual load), this irrelevant distractor could be ignored.

Interestingly, when the high and low-load trials were intermixed, a compatibility effect was found even on the trials with a high perceptual load. After a close look at the trial transition effects, it turned out that the effect was primarily driven by the trials on which a high-load trial was preceded by a low-load trial, suggesting that on those high-load trials the irrelevant distractor could not be ignored. The compatibility effect was virtually absent during a high-to-high-load transition. These results support the attentional window hypothesis. After completing a low-load trial the window is large and an irrelevant distractor falls into it on the trial that follows and is processed, even though that trial happens to a be a high-load trial. After completing a high-load trial the window is small and an irrelevant distractor falls outside of the attentional window. Surprisingly, the distractor on the next trial was still pro-

cessed when the next trial was a low-load trial. Theeuwes and colleagues (2004) explained this asymmetry by an interaction between expectancy and the perceptual load, suggesting that in low-load conditions expectancy is quickly overridden by a strong bottom-up signal.

Other evidence for the *attentional window hypothesis* was provided in a recent study by Belopolsky, Zwaan, Theeuwes, and Kramer (2007). In this study the size of the attentional window was manipulated by instructions. In a task similar to Jonides and Yantis (1988) participants had to search for a non-singleton letter that could be a color singleton on 1/N of all trials. To force participants to diffuse their attention across the whole display, in one condition they had to start searching when all the elements in the display constructed an upward-pointing triangle and to withhold their response when they constructed a downward-pointing triangle. To force participants to reduce the size of their attentional window, in another condition they had to start searching only when the fixation point was a circle. The logic was straightforward. If the size of the attentional window affects attentional capture by a color singleton, then there should be more capture when attention is diffuse and no capture when attention is focused. This is precisely what was found.

The results of Belopolsky et al. (2007) suggest that salient singletons may not capture attention when the attentional window is small. When attention is spread across the visual field allowing parallel search (as in Theeuwes, 1992, 1994, 2004), attention is captured by salient singletons. Importantly, there is no need to claim the existence of different search modes. The only thing that is under top-down control is the size of the attentional window. However, there is no top-down control within the attended window.

To summarize, the size of an attentional window is a variable that needs to be considered when attentional capture by a salient singleton is investigated. One way to reconcile different views on the extent of top-down control is to conclude that salience computations are more or less restricted to the attentional window of the observer, which is under a top-down control. Therefore, the size of the attention window also influences the processing of the first feedforward sweep of information. Within the attentional window, however, no top-down control is possible and attention is first shifted to the location of the most salient feature.

5. Attentional capture and the N2pc

Recently, there has been an increased interest in investigating the mechanisms underlying attentional capture using event-related potentials (ERP, Eimer & Kiss, 2008; Hickey et al., 2006; Kiss, Jolicoeur, Dell'Acqua, & Eimer, 2008). In particular, studies have focused on a component called the 'N2pc' that is considered an index of the deployment of spatial attention. The N2pc is defined as a larger negative voltage at electrodes contralateral to an attended stimulus and is thought to reflect the attentional selection of an item via the suppression of surrounding items (Luck, Girelli, McDermott, & Ford, 1997). Hickey and colleagues (2006) investigated whether a salient color singleton in the attentional capture paradigm elicits an N2pc. By placing the target on the vertical meridian and the distractor at a lateral location, any N2pc would be attributable to the distractor, since stimuli on the vertical meridian do not elicit an N2pc (Woodman & Luck, 2003). Distractor singletons indeed elicited a robust N2pc, which shows that salient distractors capture attention when they are defined by an irrelevant visual feature. Moreover, when target and distractor were presented in opposite hemifields, an N2pc was observed for both stimuli, with the distractor-elicited N2pc preceding the target-elicited N2pc. This indicates that participants shifted their attention

first to the distractor and then to the target, in line with the idea that irrelevant salient singletons capture attention independently of the top-down set.

Although finding an N2pc provides evidence that spatial attention shifted to a location, it has to be noted that the absence of an N2pc does not imply that attention did not shift (Luck & Hillyard, 1994). As discussed above, the contingent capture hypothesis states that only the salient features that are relevant to the "attentional set" of the observer capture attention. Studies that combined "contingent capture" conditions with ERP recordings found no N2pc (Eimer & Kiss, 2008; Eimer, Kiss, Press, & Sauter, in press; Kiss et al., 2008). This has been shown in a spatial cueing study on the influence of uninformative color singleton cues that preceded target arrays (Eimer & Kiss, 2008) and in singleton visual search tasks (Kiss et al., 2008). In the study of Kiss and colleagues (2008), irrelevant singletons with a different color than the target did not capture attention and evoked no N2pc. However, as noted above, it is still possible that attentional selection occurred in these studies, although not reflected in the presence of an N2pc (for further discussion, see Theeuwes, Van der Burg, and Belopolsky (2008)).

To conclude, whereas the presence of the N2pc seems to be a useful additional index of which element captures attention, absence of the N2pc does not inform us about a possible lack of attentional allocation. The finding that that the irrelevant salient singleton elicits an N2pc like in the study of Hickey and colleagues (2006), seems to provide additional information on the time-course of the relative contribution of bottom-up and top-down control of selection that cannot be obtained by only looking at behavioral responses.

6. Top-down and bottom-up control of eye movements

Attention and eye movements are known to be highly related. According to the premotor theory of Rizzolatti and colleagues (Rizzolatti, Riggio, Dascola, & Umilta, 1987; Rizzolatti, Riggio, & Sheliga, 1994), shifts of attention are a by-product of the preparation of an eye movement to a particular location in space. Indeed, the preparation of a saccade towards a specific location produces a processing advantage for stimuli positioned there (Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995; Van der Stigchel & Theeuwes, 2005a). Moreover, directing spatial attention to a location generates activation within the oculomotor system leading to a modulation of saccade trajectories produced by the shift of spatial attention (Sheliga, Riggio, Craighero, & Rizzolatti, 1995; Sheliga, Riggio, & Rizzolatti, 1994, 1995; Van der Stigchel & Theeuwes, 2007). There is also ample neurophysiological evidence for a connection between spatial attention and eye movements. For example, Corbetta and colleagues (1998) showed overlapping activation in both parietal and frontal lobes in conditions in which participants either shifted attention or shifted the eyes. Furthermore, microstimulation of the FEF, an area involved in saccade preparation (Bruce, Goldberg, Bushnell, & Stanton, 1985), enhances visual excitability and attention (Armstrong, Fitzgerald, & Moore, 2006; Moore & Armstrong, 2003; Moore & Fallah, 2004). All these studies point to a link between spatial attention and eye movements.

The relative contribution of bottom-up and top-down control of selection can therefore be investigated by recording eye movements. Although there is not a one-to-one relation between the locus of attention and the location of the eye movement (Theeuwes, de Vries, & Godijn, 2003; Van der Stigchel & Theeuwes, 2005a), the allocation of attention is reflected not only in the location of the eye movement, but also in the saccade latency and in the saccade trajectory. In particular, the temporal aspects of visual selection can be measured by comparing fast and slow eye movements. In

this section, we discuss evidence that early oculomotor selection is dominated by the feedforward sweep in which selection is driven by bottom-up salience. Later in processing, when recurrent processing has already started, top-down factors bias attentional selection.

Part of the evidence for the influence of timing on attentional selection comes from visual search experiments in which eye movements were registered. In a series of experiments van Zoest and colleagues (van Zoest & Donk, 2005; van Zoest, Donk, & Theeuwes, 2004) showed that stimulus-driven control dominates selection early on, whereas goal-driven control dominates later selection. In their experiments, participants always searched for a target singleton defined by either a unique color or orientation. This target was presented among homogenous non-targets. On some trials, a distractor was present that was more salient, equally salient or less salient than the target. Results showed that eye movements with short latencies were completely stimulus-driven, because only the relative salience of target and distractor determined which element the saccade went to in this time window (see Fig. 2). However, no effect of salience was observed in cases of eye movements occurring later in time. In this time window, eye movements were more goal-driven and less influenced by the feedforward sweep (see also Ludwig and Gilchrist (2002), Mulckhuyse, Van Zoest, and Theeuwes (2008)).

Similar effects were also observed in a variant of the attentional capture paradigm, the so-called 'oculomotor capture' paradigm (Godijn & Theeuwes, 2002; Theeuwes et al., 1998). In this task, observers viewed displays containing a number of gray circles positioned on an imaginary circle around a central fixation point. After a fixed period, all circles changed color except one (the target circle). Upon the presentation of the target, on some trials an additional irrelevant red circle was presented with abrupt onset in the display. In 30–40% of trials in which the additional onset circle was presented, participants did not saccade to the target element, but made an eye movement to the onset distractor element: the eye was 'captured' by the onset distractor. Consistent with the idea that initial selection is stimulus-driven, latencies of the saccades directed to the irrelevant onset are generally shorter than the latencies directed to the target.

Not only the direction of a saccade but also its trajectory can be used as a measure of competition between top-down and bottom-up selection (for a review, see Van der Stigchel, Meeter, and Theeu-

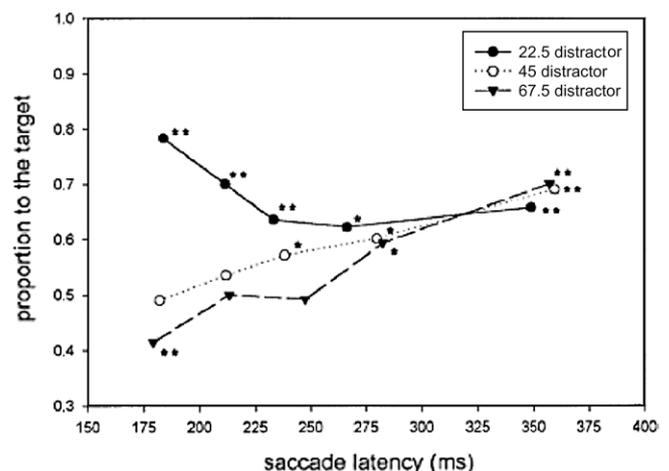
Fig. 2. The percentage of saccades directed towards the target (45°) in the three conditions as a function of time (adopted from van Zoest, Donk, & Theeuwes, 2004). The distractors presented were rotated 22.5°, 45°, or 67.5° of arc relative to the vertical, in the opposite direction from the target. As the screen was filled with vertical elements, the 67.5° distractors were relatively the most salient.

wes (2006)). Saccades are never entirely straight but curve in ways that vary from observer to observer. In addition to this normal curvature, the presence of distractors in the visual field causes saccades to deviate from the path they would have taken without distractors. These deviations from a normal trajectory are regarded as a reflection of competitive processes in the oculomotor system. In visual search tasks, saccade trajectories to the target show two types of characteristics when a distractor is present: deviations *towards* and *away* from the distractor (Doyle & Walker, 2001, 2002; Godijn & Theeuwes, 2002; Ludwig & Gilchrist, 2003; McPeek, Skavenski, & Nakayama, 2000; Van der Stigchel, Meeter, & Theeuwes, 2007a, 2007b; Van der Stigchel & Theeuwes, 2005b; Walker, McSorley, & Haggard, 2006). It has been suggested that deviation towards the distractor results when a saccade is launched before competition between populations in the oculomotor system is resolved, leading to a saccade to the average of the two coded saccades (McSorley, Haggard, & Walker, 2006; Van der Stigchel et al., 2006). When there is enough time to allow top-down preparation of the saccade, inhibitory processing may suppress the irrelevant oculomotor activity at the location of the distractor, causing the eyes to deviate away from this location (McSorley et al., 2006; Van der Stigchel et al., 2006).

Further evidence for this idea comes from studies of the 'global effect'. This phenomenon occurs when a target and an irrelevant distractor element are placed close to each other, typically within 20° or 30° of angular distance (Coren & Hoenig, 1972; Van der Stigchel & Theeuwes, 2005b; Walker, Deubel, Schneider, & Findlay, 1997). In this situation, eye movements to the target generally land on an intermediate location between target and distractor. These findings support a 'center of gravity' account, which states that the saccade endpoint is based on the relative salience of the elements in the saccade map (Coren & Hoenig, 1972). A crucial finding is that the global effect is more frequent for short saccade latencies than for long latencies (Ottes, Van Gisbergen, & Eggermont, 1985; Van der Stigchel & Theeuwes, 2005b).

To conclude, findings from eye movement research support the conclusion that the relative contribution of stimulus-driven and goal-driven control in visual selection depends on the latency of the response. Eye movements made with a short latency seem to be made solely on the basis of the bottom-up signal, whereas slower eye movements reflect both bottom-up and top-down salience.

7. Top-down control of attention in the brain

The behavioral evidence reviewed above seems to suggest that fast responses emitted immediately following display onset are solely based on bottom-up salience. When the response is made later in time top-down factors also start influencing visual selection. If this is the case, one would predict that top-down control cannot bias brain activity in visual processing areas before the display is presented or during initial processing of the display, i.e., the feedforward sweep. This prediction has been tested repeatedly using functional magnetic resonance imaging (fMRI) and ERPs. While behavioral findings reviewed above suggest no influence of top-down modulation, results from fMRI and ERP studies are much more equivocal.

Numerous studies have revealed the brain network underlying the top-down control of spatial attention (for a review, see Corbetta and Shulman (2002)). A dorsal frontoparietal network, including the intraparietal sulcus (IPS) and the superior parietal lobule (SPL) in the posterior parietal cortex (PPC), and the frontal eye field (FEF) located in the frontal cortex, is involved in orienting attention towards relevant stimuli under top-down control. It has been suggested that neural responses in the SPL and FEF (and in

supplementary eye fields) bias activity in the visual cortex (e.g., Kastner, Pinsk, De Weerd, Desimone, & Ungerleider, 1999), in which retinotopic regions representing the cued location show enhanced responses both in the presence (Brefczynski & DeYoe, 1999; Somers, Dale, Seiffert, & Tootell, 1999; Tootell et al., 1998) as well as in the absence (i.e., on the basis of instruction, Hopfinger, Buonocore, & Mangun, 2000; Kastner et al., 1999) of visual stimuli.

Although research on top-down control of attention in the brain has primarily focused on visual-spatial attention, it has been suggested that top-down attention to non-spatial visual features recruits the same frontoparietal network as the one revealed by spatial attention tasks (Giesbrecht, Woldorff, Song, & Mangun, 2003). There is also accumulating evidence for involvement of this general attentional control system in biasing the processing in the feature selective areas of visual cortex prior to the presentation of the target. For example, in an influential PET study Corbetta and colleagues (1991) showed that attending to a specific feature, like color or motion, enhances activity in visual areas that are specialized for processing that feature. Subsequently, several MRI studies have corroborated these findings, showing that attending to the color or motion of stimuli enhances activity before the target is presented in, respectively, the color-selective area V4/V8 (Chawla, Rees, & Friston, 1999; Clark et al., 1997; Schoenfeld et al., 2007) and the motion-selective hMT+/V5 complex (Beauchamp, Cox, & DeYoe, 1997; Chawla et al., 1999; O'Craven, Rosen, Kwong, Treisman, & Savoy, 1997; Saenz, Buracas, & Boynton, 2002; Schoenfeld et al., 2007; Shulman et al., 1999).

These results clearly demonstrate that attending to a feature modulates activity in visual areas specialized for processing that feature. However, given that the target features were often present in the display and the poor temporal resolution of fMRI, it is possible that the observed effects of feature-based attention occur at a stage relatively late in processing. Such an interpretation, however, is unlikely for studies that have focused on measuring brain activity in response to the cue, thus deconvolving the cue and target-related activations. These studies found that even in the absence of corresponding sensory stimulation, the instruction to attend to color or motion feature activated their specialized processing regions (V4 and MT, respectively, Chawla et al., 1999; Giesbrecht et al., 2003; Shulman et al., 1999).

Top-down attentional control to non-spatial visual features has also been examined using ERPs. In contrast to spatial attention that modulates ERP components as early as 80 ms post-stimulus, attention to non-spatial attributes (i.e., color, shape, spatial frequency, motion or orientation) was shown to elicit broad negative deflection around 150–350 ms focused over posterior occipital sites (the selection negativity, SN) (Anllo-Vento & Hillyard, 1996; Harter & Aine, 1984). The SN has been interpreted as reflecting the attentional facilitation of feature-specific visual processing. The neural generators of the SN differ depending on the attended feature. For example, dipole source modeling in a study by Anllo-Vento, Luck, and Hillyard (1998), where participants were instructed to respond to stimuli of a specific color, put the origins of the SN in the collateral sulcus, an area in the ventral visual processing stream associated with color. Scalp distributions of the SN in a study where participants were instructed to attend to a specific motion suggested a more dorsal source, near cortical areas responsible for motion perception (Anllo-Vento & Hillyard, 1996).

Reports of earlier non-spatial attentional modulations are relatively scarce. As previously demonstrated for spatial attentional selection, the C1 component was found to be unresponsive to non-spatial attention (Anllo-Vento et al., 1998). In the same study a color cue resulted in a small early posterior positivity at 130 ms after stimulus presentation. Dipole source localization pointed to origins somewhere in dorsal extrastriate visual areas V2, V3, or V3a. Similar results were reported by Taylor (2002) who found

an enlarged P1 for stimuli exhibiting attended features; and Eimer (1997) who found positive deflections on frontal electrodes around 150–200 ms for stimuli possessing attended features. However, in the latter study these positive deflections disappeared when the participant's attention was cued on a trial-by-trial basis (e.g., a cue informs the participant whether to attend to blue or red on each trial) as opposed to participants attending the same stimulus attribute for an entire experimental block. The SN found in this study was also weakened when cues varied the attribute that participants needed to attend to. This finding casts some doubt on the suggestion that non-spatial attentional modulations of ERP were due to top-down enhancement of feature selective areas, since most studies used a blocked design (i.e., sustained attention to a single attribute throughout an experimental block). Alternatively, the observed attentional modulation could be at least partially due to bottom-up priming effects resulting from processing the same target on a previous trial.

Although both fMRI and ERP studies convincingly showed a possibility of top-down modulation of feature selective areas, the evidence from attentional capture studies discussed above shows that this enhanced visual activity induced by attending to a specific target feature cannot prevent capture by salient distractors in other dimensions. Which brain areas are responsible for such automatic capture of attention are not well known. The studies that have compared automatic shifts with voluntary shifts using the Posner cueing paradigm have found a large overlap between the automatic and voluntary orienting networks (Kim et al., 1999; Peelen, Heslenfeld, & Theeuwes, 2004).

More specific information on the automatic orienting network has been revealed by examining situations in which attention is captured by an irrelevant singleton. One fMRI study that examined this issue showed that attentional capture by a color singleton enhanced activity in the left lateral precentral gyrus of the frontal cortex and in areas of the SPL (De Fockert, Rees, Frith, & Lavie, 2004). As activity in the SPL has been associated with attentional shifts (e.g., Corbetta & Shulman, 2002), the finding that the SPL activity is enhanced in the presence of an irrelevant singleton distractor shows that spatial attention was indeed allocated to the singleton distractor. Interestingly, the interference of the color singleton with search performance reduced when frontal activity was increased. This negative correlation between magnitude of behavioral interference by the color singleton and strength of frontal activity suggests that this frontal area plays an important role in the top-down control of interference by irrelevant salient stimuli. In contrast to the frontal areas, activity in the parietal areas did not correlate with the behavioral interference. This suggests that whereas parietal attentional areas subserved the attentional shift to an irrelevant singleton, the magnitude of the actual interference by the singleton is determined by the involvement of frontal areas.

Recent studies have observed concurrent activation in the temporoparietal junction (TPJ) and ventral frontal cortex (VFC) when attention is captured by a behaviorally relevant stimulus (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Corbetta & Shulman, 2002; Serences et al., 2005). In particular, TPJ has been hypothesized to be part of a right-lateralized ventral frontoparietal network that detects behaviorally relevant stimuli (Corbetta & Shulman, 2002; Shulman et al., 2003). Additionally, a study by Kincade and colleagues (2005) underscored the importance of behavioral relevance for TPJ involvement in exogenous orienting, by showing that TPJ activity was increased by orienting to targets at unattended locations, but not to task-irrelevant color singletons. In sum, detection of behaviorally relevant, salient stimuli seems to be mediated by a right-lateralized ventral frontoparietal network with areas in the ventral frontal cortex (VFC) and the temporoparietal junction (TPJ) as core regions.

In conclusion, although both fMRI and ERP studies convincingly showed a possibility of top-down modulation of feature selective areas, the behavioral findings from attentional capture paradigms suggest that this neural modulation does not necessarily influence initial selection. The actual orienting of attention on the basis of bottom-up factors appears to depend on the conjoint activity of areas in the parietal and frontal networks.

8. Conclusions

The present review of recent experimental findings suggests that the role of top-down control on spatial visual selection is not as profound as assumed by most current theories. In visual search, fore-knowledge of the target feature does not seem to increase the speed of attentional deployment, but affects primarily the post-selection processes. On the other hand, being presented with the exact feature of the upcoming target, speeds up its localization during visual search even when such information contradicts top-down settings (Theeuwes et al., 2006). Therefore, what was previously thought to reflect top-down control over attentional guidance in visual search could be explained by bottom-up priming effects (e.g., Maljkovic & Nakayama, 1994, 2000; Meeter & Olivers, 2006; Olivers & Meeter, 2006).

In other words, it appears that top-down control for non-spatial information cannot modulate the initial sweep of information, which is primarily based on bottom-up salience. The salience map encodes the salience of objects in their visual environment. Neurons in this map compete among each other giving rise to a single winning location (cf. winner take all) that contains the most salient element. In line with the classic two-process theories of attention (e.g., Broadbent, 1958), the salience map is the result of preattentive parallel encoding across the visual field calculating differences in simple visual features such as intensity, contrast, color and orientation (Itti & Koch, 2001; Koch & Ullman, 1985). In the first feedforward sweep, attention is captured in a bottom-up fashion to the most salient location. Top-down control can influence selection only after the first sweep is completed.

This conclusion is corroborated by studies on attentional capture showing that during parallel visual search an irrelevant salient singleton captures attention independently of the top-down set (Theeuwes, 1991, 1992). Later in the trial, however, through recurrent processing the top-down control begins to have an effect allowing disengaging and redirecting attention to the target location (Theeuwes, 1994; Theeuwes et al., 2000). The emergence of top-down control with time has been powerfully illustrated by the finding that slow eye movements are controlled in a top-down way, while fast eye movements are completely driven by bottom-up salience signals (van Zoest, Donk, & Theeuwes, 2004).

Contrary to the seeming lack of top-down control for non-spatial features, many studies have showed that attention can be voluntarily allocated to a location in space and enhance visual processing at that location (Carrasco, Giordano, & McElree, 2004; Heinze et al., 1994; Posner, 1980). It has been demonstrated that focusing attention at a location can also preclude attentional capture by irrelevant salient singletons (Theeuwes, 1991; Yantis & Egeth, 1999; Yantis & Jonides, 1990). Extending this finding, recent studies on attentional capture showed that salience computations are more or less restricted to the attentional window, an area of visual space which receives priority in information sampling. If attention is diffuse, any irrelevant salient item competes for visual selection and the selection is controlled in bottom-up fashion. If attention is focused, primarily items that fall within the attentional window compete for selection (Belopolsky et al., 2007).

Therefore, top-down control appears to be limited both temporally and spatially. Interestingly, in apparent contradiction to these

behavioral and eye movement findings several brain imaging studies demonstrated that top-down control for non-spatial feature results in activation of feature selective areas in the brain (e.g., Anllo-Vento et al., 1998; Giesbrecht et al., 2003). Further research is needed to resolve this contradiction. One possible explanation is that most of these studies did not control for priming effects that could account for the observed findings. The direct comparison of trial-by-trial cueing of target feature and sustained presentation of target feature throughout a block of trials could provide an insight on the relative contribution of priming and top-down control. It is possible that if priming effects are controlled for, as in Eimer's (1997) study, early modulation of the feature selective areas would disappear. In addition, though some fMRI studies have shown that top-down expectancy for non-spatial features may alter neural modulation, the behavioral findings from attentional capture paradigms suggest that this neural modulation does not necessarily influence initial selection. Indeed, as argued by Martinez and Hillyard (2005) it is possible that the non-spatial attentional effects observed with fMRI represents a top-down bias producing a sustained attention-related activity without necessarily modulating the initial stimulus-evoked response.

To sum up, the purpose of this review was to draw attention to the accumulating evidence regarding the spatial and temporal limits of top-down control of visual attention. Current theories of visual attention need to be revised to accommodate these limitations. The role of bottom-up processes in the brain networks associated with top-down control also needs to be clarified.

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