

Visual search and selective attention

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Visual search is a key paradigm in attention research that has proved to be a test bed for competing theories of selective attention. The starting point for most current theories of visual search has been Treisman's "feature integration theory" of visual attention (e.g., Treisman & Gelade, 1980). A number of key issues that have been raised in attempts to test this theory are still pertinent questions of research today: (1) The role and (mode of) function of bottom-up and top-down mechanisms in controlling or "guiding" visual search; (2) in particular, the role and function of implicit and explicit memory mechanisms; (3) the implementation of these mechanisms in the brain; and (4) the simulation of visual search processes in computational or, respectively, neurocomputational (network) models. This paper provides a review of the experimental work and the—often conflicting—theoretical positions on these thematic issues, and goes on to introduce a set of papers by distinguished experts in fields designed to provide solutions to these issues.

A key paradigm in attention research, that has proved to be a test bed for competing theories of selective attention, is visual search. In the standard paradigm, the observer is presented with a display that can contain a target stimulus amongst a variable number of distractor stimuli. The total number of stimuli is referred to as the display size. The target is either present or absent, and the observers' task is to make a target-present vs. target-absent decision as rapidly and accurately as possible. (Alternatively, the search display may be presented for a limited exposure duration, and the dependent variable is the accuracy of target detection.) The time taken for these decisions (the reaction time, RT) can be graphed as a function of the display size (search RT functions). An important characteristic of such functions is its slope, that is, the search rate, measured in terms of time per display item. Based on the search RT functions obtained in a variety of search experiments, a distinction has been proposed between two modes of visual

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search (e.g., Treisman & Gelade, 1980): Parallel and serial. If the search function increases only little with increasing display size (search rates < 10 ms/item), it is assumed that all items in the display are searched simultaneously, that is, in “parallel” (“efficiently”). In contrast, if the search functions exhibit a linear increase (search rates > 10 ms/item), it is assumed that the individual items are searched successively, that is, the search operates “serially” (“inefficiently”).

This does not explain, of course, why some searches can operate efficiently, in parallel, while others operate inefficiently, (strictly) serially, and why, in some tasks, the search efficiency is found to lie in between these extremes. In order to explain this variability, a number of theories of visual search have been proposed, which, in essence, are general theories of selective visual attention. The starting point for most current theories of visual search has been Anne Treisman’s “feature integration theory” of visual attention (e.g., Treisman & Gelade, 1980; see below). This theory led to a boom in studies on visual search; for example, between 1980 and 2000, the number of published studies rose by a factor of 10. A number of key issues that have been raised in attempts to test this theory are still pertinent questions of research today: (1) The role and (mode of) function of bottom-up and top-down mechanisms in controlling or “guiding” visual search; (2) in particular, the role and function of implicit and explicit memory mechanisms; (3) the implementation of these mechanisms in the brain; and (4) the simulation of visual search processes in computational or, respectively, neurocomputational (network) models.

The present *Visual Cognition* Special Issue presents a set of papers concerned with these four issues. The papers are based on the presentations given by some 35 leading visual-search experts worldwide, from a variety of disciplines—including experimental and neuropsychology, electro- and neurophysiology, functional imaging, and computational modelling—at the “Visual Search and Selective Attention” symposium held at Holzhausen am Ammersee, near Munich, Germany, June 6–10, 2003 (“Munich Visual Search Symposium”, for short¹). The aim of this meeting was to foster a dialogue amongst these experts, in order to contribute to identifying theoretically important joint issues and discuss ways of how these issues can be resolved by using convergent, integrated methodologies.

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THE SPECIAL ISSUE

This Special Issue opens with Anne Treisman's (2006 this issue) invited "Special Lecture", which provides an up-to-date overview of her research, over 25 years, and her current theoretical stance on visual search. In particular, Treisman considers "how the deployment of attention determines what we see". She assumes that attention can be focused narrowly on a single object, spread over several objects or distributed over the scene as a whole—with consequences for what we see. Based on an extensive review of her ground-breaking original work and her recent work, she argues that focused attention is used in feature binding. In contrast, distributed attention (automatically) provides a statistical description of sets of similar objects and gives the gist of the scene, which may be inferred from sets of features registered in parallel.

The four subsequent sections of this Special Issue present papers that focus on the same four themes discussed at the Munich Visual Search Symposium (see above): I Preattentive processing and the control of visual search; II the role of memory in the guidance of visual search; III brain mechanisms of visual search; and IV neurocomputational modelling of visual search. What follows is a brief introduction to these thematic issues, along with a summary of the, often controversial, standpoints of the various experts on these issues.

I. Preattentive processing and the control of visual search

Since the beginnings of Cognitive Psychology, theories of perception have drawn a distinction between preattentive and attentional processes (e.g., Neisser, 1967). On these theories, the earliest stages of the visual system comprise preattentive processes that are applied uniformly to all input signals. Attentional processes, by contrast, involve more complex computations that can only be applied to a selected part of the preattentive output. The investigation of the nature of preattentive processing aims at determining the functional role of the preattentive operations, that is: What is the visual system able to achieve without, or prior to, the allocation of focal attention?

Registration of basic features. Two main functions of preattentive processes in vision have been distinguished. The first is to extract basic attributes, or "features", of the input signals. Since preattentive processes code signals across the whole visual field and provide the input information for object recognition and other, higher cognitive processes, they are limited to operations that can be implemented in parallel and executed rapidly.

Experiments on visual search have revealed a set of visual features that are registered preattentively (in parallel and rapidly), including luminance, colour, orientation, motion direction, and velocity, as well as some simple aspects of form (see Wolfe, 1998). These basic features generally correspond with stimulus properties by which single cells in early visual areas can be activated.

According to some theories (e.g., Treisman & Gelade, 1980; Wolfe, Cave, & Franzel, 1989), the output of preattentive processing consists of a set of spatiotopically organized feature maps that represent the location of each basic (luminance, colour, orientation, etc.) feature within the visual field. There is also evidence that preattentive processing can extract more complex configurations such as three-dimensional form (Enns & Rensink, 1990) and topological properties (Chen & Zhou, 1997). In addition, individual preattentively registered items can be organized in groups if they share features (Baylis & Driver, 1992; Harms & Bundesen, 1983; Kim & Cave, 1999) or form connected wholes (Egly, Driver, & Rafal, 1994; Kramer & Watson, 1996). Based on evidence that preattentive processes can also complete occluded contours, He and Nakayama (1992) proposed that the output of the preattentive processes comprises not only of a set of feature maps, but also a representation of (object) surfaces.

Guidance of attention. Besides rendering an “elementary” representation of the visual field, the second main function of preattentive processes is the guiding of focal-attentional processes to the most important or “promising” information within this representation. The development of models of visual processing reveals an interesting tradeoff between these two functions: If the output of preattentive processing is assumed to only represent basic visual features, so that the essential operations of object recognition are left to attentional processes, focal attention must be directed rapidly to the (potentially) most “meaningful” parts of the field, so that the objects located there can be identified with minimal delay.

Preattentive processes must guarantee effective allocation of focal attention under two very different conditions. First, they must mediate the directing of attention to objects whose defining features are not predictable. This data-driven or bottom-up allocation of attention is achieved by detecting simple features (or, respectively, their locations) that differ from the surrounding features in a “salient” manner (e.g., Nothdurft, 1991). The parallel computation of feature contrast, or salience, signals can be a very effective means for localizing features that ought to be processed attentionally; however, at the same time it can delay the identification of a target object when there is also a distractor in the field that is characterized by a salient feature (Theeuwes, 1991, 1992). Numerous investigations had been concerned with the question under which conditions focal attention is

“attracted” by a salient feature (or object) and whether the mechanisms that direct focal attention to salient features (or objects) are always and invariably operating or whether they can be modulated by the task set (e.g., Bacon & Egeth, 1997; Yantis, 1993).

Under other conditions, the appearance of a particular object, or a particular type of object, can be predicted. In such situations, preattentive processes must be able in advance to set the processing (top-down) for the corresponding object and initiate the allocation of focal attention upon its appearance. This can be achieved by linking the allocation of attention to a feature value defining the target object, such as blue or vertical (Folk & Remington, 1998), or to a defining feature dimension, such as colour or orientation (Müller, Reimann & Krummenacher, 2003). Although the top-down allocation of attention is based, as a rule, on the (conscious) intention to search for a certain type of target, it can also be initiated by implicit processes. If the preceding search targets exhibit a certain feature (even a response-irrelevant feature), or are defined within a certain dimension, attention is automatically guided more effectively to the next target if this is also characterized by the same feature or feature dimension (Krummenacher, Müller, & Heller, 2001; Maljkovic & Nakayama, 1994, 2000; Müller, Heller, & Ziegler, 1995).

An important question for theories of preattentive vision concerns the interaction between top-down controlled allocation of attention to expected targets and bottom-up driven allocation to unexpected targets. What is required is an appropriate balance between these two modes of guidance, in order to guarantee that the limited processing resources at higher stages of vision are devoted to the most informative part of the visual input. While there is a broad consensus that preattentive processes can guide visual search (i.e., the serial allocation of focal attention), there are a number of open questions concerning the interaction between top-down and bottom-up processing in the control of search, the top-down modifiability of preattentive processes, the interplay of feature- and dimension-based set (processes), etc. Further open questions concern the complexity of the preattentively computed “features”. All these issues are addressed by the papers collected in the first section of this Special Issue, “Preattentive processing and the control of visual search”.

The first set of three papers (Folk & Remington; Theeuwes, Reimann & Mortier; Müller & Krummenacher) is concerned with the issue whether and to what extent preattentive processing is top-down modulable.

More specifically, C. L. Folk and R. Remington (2006 this issue) ask to which degree the preattentive detection of “singletons” elicits an involuntary shift of spatial attention (i.e., “attentional capture”) that is immune from top-down modulation. According to their “contingent-capture” perspective, preattentive processing can produce attentional capture, but such capture is

contingent on whether the eliciting stimulus carries a feature property consistent with the current attentional set. This account has been challenged recently by proponents of the “pure- (i.e., bottom-up driven-) capture” perspective, who have argued that the evidence for contingencies in attentional capture actually reflects the rapid disengagement and recovery from capture. Folk and Remington present new experimental evidence to counter this challenge.

One of the strongest proponents of the pure-capture view is Theeuwes. J. Theeuwes, B. Reimann, and K. Mortier (2006 this issue) reinvestigated the effect of top-down knowledge of the target-defining dimension on visual search for singleton feature (“pop-out”) targets. They report that, when the task required simple detection, advance cueing of the dimension of the upcoming singleton resulted in cueing costs and benefits; however, when the response requirements were changed (“compound” task, in which the target-defining attributes are independent of those determining the response), advance cueing failed to have a significant effect. On this basis, Theeuwes et al. reassert their position that top-down knowledge cannot guide search for feature singletons (which is, however, influenced by bottom-up priming effects when the target-defining dimension is repeated across trials). Theeuwes et al. conclude that effects often attributed to early top-down guidance may in fact represent effects that occur later, after attentional selection, in processing.

H. J. Müller and J. Krummenacher (2006 this issue) respond to this challenge by asking whether the locus of the “dimension-based attention” effects originally described by Müller and his colleagues (including their top-down modifiability by advance cues) are preattentive or postselective in nature. Müller and his colleagues have explained these effects in terms of a “dimension-weighting” account, according to which these effects arise at a preattentive, perceptual stage of saliency coding. In contrast, Cohen (e.g., Cohen & Magen, 1999) and Theeuwes have recently argued that these effects are postselective, response-related in nature. In their paper, Müller and Krummenacher critically evaluate these challenges and put forward counterarguments, based partly on new data, in support of the view that dimensional weighting operates at a preattentive stage of processing (without denying the possibility of weighting processes also operating post selection).

A further set of four papers (Nothdurft; Smilek, Enns, Eastwood, & Merikle; Leber & Egeth; Fanini, Nobre, & Chelazzi) is concerned with the influence of “attentional set” for the control of search behaviour.

H.-C. Nothdurft (2006 this issue) provides a closer consideration of the role of salience for the selection of predefined targets in visual search. His experiments show that salience can make targets “stand out” and thus control the selection of items that need to be inspected when a predefined target is to be searched for. Interestingly, salience detection and target

identification followed different time courses. Even typical “pop-out” targets were located faster than identified. Based on these and other findings, Nothdurft argues in favour of an interactive and complementary function of salience and top-down attentional guidance in visual search (where “attention settings may change salience settings”).

While top-down controlled processes may guide selective processes towards stimuli displaying target-defining properties, their mere involvement may also impede search, as reported by D. Smilek, J. T. Enns, J. D. Eastwood, and P. M. Merikle (2006 this issue). They examined whether visual search could be made more efficient by having observers give up active control over the guidance of attention (and instead allow the target to passively “pop” into their minds) or, alternatively, by making them perform a memory task concurrently with the search. Interestingly, passive instructions and a concurrent task led to more efficient performance on a hard (but not an easy) search task. Smilek et al. reason that the improved search efficiency results from a reduced reliance on slow executive control processes and a greater reliance on rapid automatic processes for directing visual attention.

The importance of executive control or (top-down) “attentional set” for search performance is further illustrated by A. B. Leber and H. E. Egeth (2006 this issue). They show that, besides the instruction and the stimulus environment, past experience (acquired over an extended period of practice) can be a critical factor for determining the set that observers bring to bear on performing a search task. In a training phase, observers could use one of two possible attentional sets (but not both) to find colour-defined targets in a rapid serial visual presentation stream of letters. In the subsequent test phase, where either set could be used, observers persisted in using their pre-established sets.

In a related vein, A. Fanini, A. C. Nobre, and L. Chelazzi (2006 this issue) used a negative priming paradigm to examine whether feature-based (top-down) attentional set can lead to selective processing of the task-relevant (e.g., colour) attribute of a single object and/or suppression of its irrelevant features (e.g., direction of motion or orientation). The results indicate that individual features of a single object can indeed undergo different processing fates as a result of attention: One may be made available to response selection stages (facilitation), while others are actively blocked (inhibition).

Two further papers (Pomerantz; Cave & Batty) are concerned with visual “primitives” that may form the more or less complex representations on which visual search processes actually operate—“colour as a Gestalt” and, respectively, stimuli that evoke strong threat-related emotions.

J. R. Pomerantz (2006 this issue) argues that colour perception meets the customary criteria for Gestalts at least as well as shape perception does, in that colour emerges from nonadditive combination of wavelengths in the

perceptual system and results in novel, emergent features. Thus, colour should be thought of not as a basic stimulus feature, but rather as a complex conjunction of wavelengths that are integrated in perceptual processing. As a Gestalt, however, colour serves as a psychological primitive and so, as with Gestalts in form perception, may lead to “pop out” in visual search.

Recently, there have been claims (e.g., Fox et al., 2000; Öhman, Lundqvist & Esteves, 2001) that social stimuli, such as those evoking strong emotions or threat, may also be perceptual primitives that are processed preattentively (e.g., detected more rapidly than neutral stimuli) and, thus, especially effective at capturing attention. In their contribution, K. R. Cave and M. J. Batty (2006 this issue) take issue with these claims. A critical evaluation of the relevant studies leads them to argue that there is no evidence that the threatening nature of stimuli is detected preattentively. There is evidence, however, that observers can learn to associate particular features, combinations of features, or configurations of lines with threat, and use them to *guide* search to threat-related targets.

II. The role of memory in the guidance of visual search

Inhibition of return and visual marking. A set of issues closely related to “preattentive processing” concerns the role of memory in the guidance of visual search, especially in hard search tasks that involve serial attentional processing (e.g., in terms of successive eye movements to potentially informative parts of the field). Concerning the role of memory, there are diametrically opposed positions. There is indirect experimental evidence that memory processes which prevent already searched parts of the field from being reinspected, play no role in solving such search problems. In particular, it appears that visual search can operate efficiently even when the target and the distractors unpredictably change their positions in the search display presented on a trial. This has given rise to the proposal that serial search proceeds in a “memoryless” fashion (cf. Horowitz & Wolfe, 1998). On the other hand, there is evidence that “inhibition of return” (IOR) of attention (Posner & Cohen, 1984) is also effective in the guidance of visual search, by inhibitorily marking already scanned locations and, thereby, conferring an advantage to not-yet-scanned locations for the allocation of attention (Klein, 1988; Müller & von Mühlelen, 2000; Takeda & Yagi, 2000).

Related questions concern whether and to what extent memory processes in the guidance of search are related to mechanisms of eye movement control and how large the capacity of these mechanisms is. For example, Gilchrist and Harvey (2000) observed that, in a task that required search for a target letter amongst a large number of distractor letters, refixations were rare within the first two to three saccades following inspection of an item, but afterwards occurred relatively frequently. This argues in favour of a short-

lived (oculomotor) memory of a low capacity for already fixated locations. In contrast, Peterson, Kramer, Wang, Irwin, and McCarley (2001) found that, when observers searched for a “T” amongst “L”s, refixations occurred less frequently (even after long intervals during which up to 11 distractors were scanned) than would have been expected on the basis of a memoryless model of visual search. This argues in favour of a longer lasting memory of relatively large capacity.

Another, controversial form of search guidance has been proposed by Watson and Humphreys (1997), namely, the parallel “visual marking” of distractors in the search field: If, in conjunction search (e.g., for a red “X” amongst blue “X”s and red “O”s), a subset of the distractors (red “O”s) are presented prior to the presentation of the whole display (which includes the target), a search process that is normally inefficient is turned into an efficient search. Watson and Humphreys explained this in terms of the inhibitory marking (of the locations) of the prepresented distractors, as a result of which search for a conjunction target amongst all distractors is reduced to search for a simple feature target amongst the additional, later presented distractors (search for a red “X” amongst blue “X”s). However, whether Watson and Humphreys’ findings are indeed based on the—memory-dependent—parallel suppression of distractor positions or, alternatively, the attentional prioritization of the display items that onset later (accompanied by abrupt luminance change) (Donk & Theeuwes, 2001), is controversial. (See also Jiang, Chun, & Marks, 2002, who argued that the findings of Watson and Humphreys reflect a special memory for stimulus asynchronies.)

Scene-based memory. The idea, advocated by Watson and Humphreys (1997), of an inhibitory visual marking implies a (more or less implicit) memory of the search “scene”. That a memory for the search scene exists is also documented by other studies of visual search for pop-out targets (Kumada & Humphreys, 2002; Maljkovic & Nakayama, 1996). These studies have shown that detection of a salient target on a given trial that appears at the same position as a target on previous trials is expedited relative to the detection of a target at a previous nontarget (or empty) position; in contrast, detection is delayed if a target appears at the position of a previously salient, but to-be-ignored distractor, relative to detection of a target at a nondistractor position. Such positive and negative effects on the detection of a target on the current trial could be traced back across five to eight previous trials (Maljkovic & Nakayama, 1996). The long persistence of these effects suggests that they are based on (most likely implicit) memory mechanisms of search guidance. That such mechanisms can also represent the arrangement of items in complex search scenes, is suggested by Chun and Jiang (1998). They found that the search (e.g., for an orthogonally rotated “T” amongst orthogonally rotated “L”s) on a trial was expedited if a

certain, complex arrangement of display items (targets und distractors) was repeated, with some five repetitions of the arrangement (one repetition each per block of 24 trials) being sufficient to generate the learning effect.

With regard to scene-based memory, another controversial issue is: How much content-based information is retained from the (oculomotor) scanning of a natural scene in an enduring (implicit or explicit) representation? One position states that visual (object) representations disintegrate as soon as focal attention is withdrawn from an object, so that the scene-based representation is rather “poor” (e.g., Rensink, 2000a; Rensink, O’Regan, & Clark, 1997). An alternative position is that visual representations do not necessarily disintegrate after the withdrawal of attention; rather, representations from already attended regions can be accumulated within scene-based memory (e.g., Hollingworth, & Henderson, 2002; Hollingworth, Williams, & Henderson, 2001).

In summary, there is evidence that a set of implicit (i.e., preattentive), as well as explicit, memory mechanisms are involved in the guidance of visual search. Open questions are: How many mechanisms can be distinguished? What is their decay time? How large is their capacity? and so on. These questions are considered, from different perspectives, in this second section of papers in this Special Issue.

The first set of four papers (Klein & Dukewich; Horowitz; McCarley, Kramer, Boot, Peterson, Wang, & Irwin; and Gilchrist & Harvey) are concerned with the issue of memory-based control of covert and overt (i.e., oculomotor) attentional scanning in visual search.

R. Klein and K. Dukewich (2006 this issue) ask: “Does the inspector have a memory?” They start with elaborating the distinction between serial and parallel search and argue that serial search would be more efficient, in principle, if there were a mechanism, such as IOR, for reducing reinspections of already scanned items. They then provide a critical review and meta-analysis of studies that have explored whether visual search is “amnesic”. They conclude that it rarely is; on the other hand, there is ample evidence for the operation of IOR in visual search. Finally, they suggest three approaches for future research (experimental, neuropsychological, and correlational) designed to provide convergent evidence of the role of IOR for increasing search efficiency.

The following paper, by T. S. Horowitz (2006 this issue), asks: “How much memory does visual search have?” The goal of this paper is less to find a definitive answer to this question than to redefine and clarify the terms of the debate. In particular, Horowitz proposes a formal framework, based on the “variable memory model” (Arani, Karwan, & Drury, 1984), which has three parameters—(1) encoding, (2) recall, and (3) target identification probability—and permits cumulative RT distribution functions to be generated. On this basis, the model can provide a common metric for

comparing answers to the above question across different experimental paradigms, in terms that are easy to relate to the “memory” literature.

The next two papers are concerned with the control oculomotor scanning in visual search. Based on RT evidence in a novel, multiple-target visual search task, Horowitz and Wolfe (2001) suggested that the control of attention during visual search is not guided by memory for which of the items or locations in a display have already been inspected. In their contribution, J. S. McCarley, A. F. Kramer, W. R. Boot, M. S. Peterson, R. F. Wang, and D. E. Irwin (2006 this issue) present analyses of eye movement data from a similar experiment, which suggest that RT effects in the multiple-target search task are primarily due to changes in eye movements, and that effects which appeared to reveal memory-free search were produced by changes in oculomotor scanning behaviour.

Another form of oculomotor memory revealed by the systematicity of scan paths in visual search is examined by I. D. Gilchrist and M. Harvey (2006 this issue). They report that, with regular grid-like displays, observers generated more horizontal than vertical saccades. Disruption of the grid structure modulated, but did not eliminate, this systematic scanning component. Gilchrist and Harvey take their findings to be consistent with the scan paths being partly determined by a “cognitive” strategy in visual search.

The next set of two papers (Olivers, Humphreys, & Braithwaite; Donk) are concerned with the benefit deriving from a preview of one set of search items (prior to presentation of a second set containing the target). C. N. L. Olivers, G. W. Humphreys, and J. J. Braithwaite (2006 this issue) review a series of experiments that provide evidence for the idea that, when new visual objects are prioritized in the preview paradigm, old objects are inhibited by a top-down controlled suppression mechanism (visual marking): They show that new object prioritization depends on task settings and available attentional resources (top-down control aspect) and that selection of new items is impaired when these items share features with the old items (negative carryover effects within as well as between trials; inhibitory aspect). They then reconsider the various accounts of the preview benefit (visual marking and alternative accounts) and conclude that these are not mutually exclusive and that the data are best explained by a combination of mechanisms.

This theme is taken up by M. Donk (2006 this issue), who argues that the results of recent studies cannot easily be explained by the original (Watson & Humphreys, 1997) visual-marking account. She goes on to consider three alternatives: Feature-based inhibition (the preview benefit is mediated by inhibition applied at the level of feature maps), temporal segregation (the benefit results from selective attention to one set of elements that can be perceptually segregated, on the basis of temporal-asynchrony signals, from another set), and onset capture (the benefit is mediated by onset signals

associated with the appearance of the new elements). She maintains that prioritization of new over old elements is primarily caused by onset capture; however, in line with Olivers et al. (2006 this issue), she admits that other mechanisms may play an additional role to optimize selection of the relevant subset of elements.

The final set of three papers (by Wolfe, Reinecke, & Brawn; Hollingworth; Woodman & Chun) are concerned with visual memory for (natural) scenes, short-term and long-term memory effects on search.

J. M. Wolfe, A. Reinecke, and P. Brawn (2006 this issue) investigated the role of bottlenecks in selective attention and access to visual short-term memory in observers' failure to identify clearly visible changes in otherwise stable visual displays. They found that observers failed to register a colour or orientation change in an object even if they were cued to the location of the object prior to the change occurring. This held true even with natural images. Furthermore, observers were unable to report changes that happened after attention had been directed to an object and before attention returned to that object. Wolfe et al. take these demonstrated failures to notice or identify changes to reflect "bottlenecks" in two pathways from visual input to visual experience: A "selective" pathway, which is responsible for object recognition and other operations that are limited to one item or a small group of items at any one time; and a "nonselective" pathway, which supports visual experience throughout the visual field but is capable of only a limited analysis of the input (visual short-term memory).

A. Hollingworth (2006 this issue) provides a review of recent work on the role of visual memory in scene perception and visual search. While some accounts (e.g., Rensink, 2000b; Wolfe, 1999) assume that coherent object representations in visual memory are fleeting, disintegrating upon the withdrawal of attention from an object, Hollingworth considers evidence that visual memory supports the accumulation of information from scores of individual objects in scenes, utilizing both visual short-term and long-term memory. Furthermore, he reviews evidence that memory for the spatial layout of a scene and for specific object positions can efficiently guide search within natural scenes.

The role of working (short-term) memory and long-term memory in visual search is further considered by G. F. Woodman and M. M. Chun (2006 this issue). Based on a review of recent studies, they argue that, while the working memory system is widely assumed to play a central role in the deployment of attention in visual search, this role is more complex than assumed by many current models. In particular, while (object) working memory representations of targets might be essential in guiding attention only when the identity of the target changes frequently across trials, spatial working memory is always required in (serial) visual search. Furthermore, both explicit and implicit long-term memory representations have clear

influences on visual search performance, with memory traces of attended targets and target contexts facilitating the viewing of similar scenes in future encounters. These long-term learning effects (of statistical regularities) deserve more prominent treatment in theoretical models.

III. Brain mechanisms of visual search

Over the past 25 years, behavioural research has produced a considerable amount of knowledge about the functional mechanisms of visual search. However, detailed insights into the brain mechanisms underlying search became available only during the past 5–10 years—based on approaches that combined behavioural experimental paradigms with methods for measuring neuronal functions at a variety of levels: From single cell recording through the activation of component systems to the analysis of whole system networks. These approaches made it possible for the first time to investigate the interplay of different brain areas in the dynamic control of visual search.

The cognitive neuropsychology of visual search examines patients with selective brain lesions who show specific performance deficits in visual search, ranging from difficulties with simple feature discrimination to impaired (working) memory for objects at already scanned locations. If these deficits can be related to specific brain lesions, important indications may be gained as to the role of the affected areas in visual search (e.g., Humphreys & Riddoch, 2001; Robertson & Eglin, 1993).

Electrophysiological approaches examine the EEG/MEG as well as event-related potentials (ERPs) in visual search tasks, above all to reveal the time course of the processes involved in visual search (e.g., Luck, Fan, & Hillyard, 1993; Luck & Hillyard, 1995). Specific ERP components become manifest at different points in time, and these components may be associated, in terms of time, with processes of preattentive and attentional processing. Depending on how accurately the neural generators of these components can be localized, these approaches can also provide indications as to the neuronal sites where the corresponding processes are occurring (in addition to the time at which they occur).

Neurophysiological single-cell recording studies can provide precise information as to both the neuronal loci and the time course of processing in visual search (e.g., Chelazzi, Duncan, Miller, & Desimone, 1993; Motter, 1994a, 1994b; Treue & Maunsell, 1996), but they cannot reveal the interplay among different areas involved in (controlling) the search.

However, this information can be gained by functional-imaging approaches, such as PET and fMRI. Since these methods may be employed both for the imaging of patterns of activity across the whole brain and the

detailed measurement of activation in specific cortical areas, they can provide information about the interplay among brain areas during the performance of visual search tasks as well as the areas that are specifically modulated by attention (e.g., Pollmann, Weidner, Müller, & von Cramon, 2000; Rees, Frith, & Lavie, 1997; Weidner, Pollmann, Müller, & von Cramon, 2002).

Recently, a further method: Transcranial magnetic stimulation (TMS) has been used to more precisely examine the role of certain brain areas in visual search (e.g., Walsh, Ellison, Asbridge, & Cowey, 1999). Whereas imaging research is “correlative” in nature, TMS can be applied to “causally” intervene in the processing—in that the targeted application of a time-locked magnetic impulse can simulate a temporary brain “lesion”. If the affected areas play no causal role, then such temporary lesions should have little direct influence on specific components of visual search.

The seven papers collected in this section of this Special Issue provide examples of how these new approaches are used to reveal the brain mechanisms of visual search and attentional selection.

In a programmatic paper charting the field, G. W. Humphreys, J. Hodsoll, C. N. L. Olivers, and E. Young Yoon (2006 this issue) argue that an integrative, cognitive-neuroscience approach can contribute not only information about the neural localization of processes underlying visual search, but also information about the functional nature of these processes. They go on to illustrate the value of combining evidence from behavioural studies of normal observers and studies using neuroscientific methods with regard to two issues: First, whether search for form–colour conjunctions is constrained by processes involved in binding across the two dimensions—work with patients with parietal lesions suggests that the answer is positive; and second, whether the “preview benefits” (see Donk, 2006 this issue; Olivers, Humphreys, & Braithwaite, 2006 this issue) are simply due to onset capture—convergent evidence from electrophysiological, brain-imaging, and neuropsychological work indicates that the answer is negative.

Also using a neuropsychological approach, L. C. Robertson and J. L. Brooks (2006 this issue) investigated whether feature processing, as well as feature binding (see also Humphreys, Hodsall, & Olivers, 2006 this issue), is affected in patients with spatial-attentional impairments. They show that the mechanisms underlying “pop out” continue to function in the impaired visual field, albeit at a slowed rate.

The following two studies (Lavie & de Fockert; Pollmann, Weidner, Müller, & von Cramon), used event-related fMRI to examine top-down modulation of attentional capture and dimension-specific saliency coding processes, respectively. N. Lavie and J. de Fockert (2006 this issue) report that the presence (vs. absence) of an irrelevant colour singleton distractor in a visual search task was not only associated with activity in superior parietal

cortex, in line with attentional capture, but was also associated with frontal cortex activity. Moreover, behavioural interference by the singleton was negatively correlated with frontal activity, suggesting that frontal cortex is involved in control of singleton interference (see also Folk & Remington, 2006 this issue).

S. Pollmann, R. Weidner, H. J. Müller, and D. Y. von Cramon (2006 this issue) review the evidence of a frontoposterior network of brain areas associated with changes, across trials, in the target-defining dimension in singleton feature, and conjunction, search (see also Müller & Krummenacher, 2006 this issue). They argue that anterior prefrontal components, reflecting transient bottom-up activation, are likely to be involved in the detection of change and the initiation and control of cross-dimensional attention (“weight”) shifts. However, they provide new evidence that the attentional weighting of the target-defining dimension itself is realized in terms of a modulation of the visual input areas processing the relevant dimension (e.g., area V4 for colour and V5/MT for motion).

How attention modulates neural processing in one feature dimension, namely motion, is considered by S. Treue and J. C. Martinez-Trujillo (2006 this issue). Concentrating on single-cell recordings from area MT in the extrastriate cortex of macaque monkeys trained to perform visual tasks, they review evidence that, in MT, “bottom-up” filtering processes are tightly integrated with “top-down” attentional mechanisms that together create an integrated saliency map. This topographic representation emphasizes the behavioural relevance of the sensory input, permitting neuronal processing resources to be concentrated on a small subset of the incoming information.

Authors such as Treue and Martinez Trujillo and Pollmann et al. ascribe saliency coding to areas in extrastriate cortex. This position is challenged by Li Zhaoping and R. Snowden, (2006 this issue) who propose that V1 creates a bottom-up saliency map, where saliency of any location increases with the firing rate of the most active V1 output cell responding to it, regardless of the feature selectivity of the cell. Thus, for example, a red vertical bar may have its saliency signalled by a cell tuned to red colour, or one tuned to vertical orientation, whichever cell is the most active. This predicts interference between colour and orientation features in texture segmentation tasks where bottom-up processes are important. Consistent with this prediction, Zhaoping and Snowden report that segmentation of textures of oriented bars became more difficult as the colours of the bars were randomly drawn from larger sets of colour features.

Until recently, right posterior parietal cortex has been ascribed a pre-eminent role in visual search. This view is disputed by J. O’Shea, N. G. Muggleton, A. Cowey, and V. Walsh (2006 this issue), who provide a reassessment of the roles of parietal cortex and the human frontal eye fields (FEFs). They review recent physiological and brain-imaging evidence, and

the results of a programme of TMS studies designed to directly compare the contributions of the parietal cortex and the FEFs in search. This leads them to argue that the FEFs are important for some aspects of search previously solely attributed to the parietal cortex. In particular, besides conjunction search tasks, the right FEF is activated in singleton feature search tasks that do not require eye movements; application of TMS to the right FEF slows RTs on target-present trials (in contrast to parietal cortex where both target-present and target-absent trials are affected); and search-related activation in the FEF starts as early as 40–80 ms post stimulus onset.

IV. Neurocomputational modelling of visual search

To provide explanations of the large data base that has been accumulated over 25 years of research on visual search, a variety of models have been developed. One class of model is rooted in Anne Treisman's "Feature Integration Theory" (FIT; Treisman & Gelade, 1980), which assumed a two-stage processing architecture: At the first, preattentive stage, a (limited) set of basic features are registered in parallel across the visual field; in the second, attentional stage, items are processed serially, one after the other. Accordingly, feature search operates in parallel (e.g., the time required to find a red target amongst green distractors would be independent of the display size because the target is defined by a unique basic feature—"red"); in contrast, conjunction search operates serially (e.g., the search for a "T" amongst "L"s in different orientations would increase with each additional "L", because the "L"s would have to be scanned one after the other before either the "T" is found or the search is terminated).

However, the strict dichotomy between parallel and serial searches postulated by FIT was cast into doubt by findings that performance in various search tasks could not be neatly assigned to one or the other category. In particular, search can be relatively efficient in tasks in which certain types of feature information can be exploited, even if the target is not defined by a single unique feature. For example, in search for a red "O" amongst black "O"s and red "N"s, observers are able to restrict search to a subset of display items; that is, search time is only dependent on the number of "O"s—the red "N"s can be effectively excluded from the search (Egeth, Virzi, & Garbart, 1984). In addition, it is also possible to exploit multiple features—so that, for example, search for a red vertical targets amongst red horizontal and green vertical distractors can be performed very efficiently, even though the target is not defined by a single feature (Wolfe, 1992). Findings along these lines led to the development of the "Guided Search" model (GS; Wolfe, 1994; Wolfe et al., 1989). GS maintains the two-stage architecture, but assumes that the serial allocation of attention can be guided

by information from preattentive stages of processing. Cave's (1999) "FeatureGate" model implements similar ideas in a neural network.

Other models of search have avoided the notion of serial selection of specific items within a two-stage architecture—by, instead, postulating a single, parallel processing system. Information is accumulated from all items simultaneously (e.g., Eriksen & Spencer, 1969; Kinchla, 1974), and stimulus properties determine how fast an item can be classified or identified. Parallel models must be able to account for the increase in RT, or, respectively, the decrease in response accuracy, with increasing display size (without recourse to a serial processing stage along the lines of FIT and GS). Many parallel models assume that the "parallel processor" has a limited capacity (e.g., Bundesen, 1990); other models assume an essentially unlimited capacity. Although, according to these models, all items can be processed simultaneously, the result remains a signal that is embedded in a background of noise. With increasing display size, the number of sources of noise (i.e., uncertainty) increases and performance declines (Palmer, Verghese, & Pavel, 2000).

Indeed, visual search may be modelled as a signal detection problem. If the target signal is strong enough, the noise produced by the distractors will have little influence on performance. However, if the target signal is weak, more information will have to be accumulated in order to discriminate it from the background noise (Eckstein, Thomas, Palmer, & Shimozaki, 2000). Signal detection models have proved to be of particular relevance for (real-life) search tasks in which the targets are not clearly demarcated in the image (e.g., search for tumours in radiological images; Swenson & Judy, 1981).

Recently, there has been a blurring of the distinction between the model classes. For example, Bundesen (1998a, 1998b) proposed the parallel processing of item groups (instead of parallel processing of all items)—a proposal that combines aspects of serial and of parallel search models (see also Carrasco, Ponte, Rechea, & Sampedro, 1998; Grossberg, Mingolla, & Ross, 1994; Humphreys & Müller, 1993; Treisman, 1982). Moore and Wolfe (2001) proposed that, while items are selected serially, one at a time (like in FIT or GS), several items can be processed simultaneously. A "pipeline" or "car wash" facility serve as relevant metaphors: Only one car can enter the facility at a time, but several cars may be simultaneously inside it. Such a processing system displays aspects of both serial and (capacity-limited) parallel processing (Harris, Shaw, & Bates, 1979).

Besides these formal computational models of visual search, neurocomputational models have been developed increasingly over the past 15 years, to simulate processes of visual search (described by functional theories) within neuronal network systems (e.g., Cave, 1999; Deco & Zihl, 2000; Heinke, Humphreys, & di Virgilio, 2002; Humphreys & Müller, 1993; Itti & Koch, 2001). In as far as these models incorporate neuroscientifically

founded assumptions with regard to the functional architecture of the search processes (and thus display a certain degree of “realism”), they bridge the gap between behavioural experimental and computational research on the one hand and neuroscientific research on the other.

This final section “Neurocomputational modelling of visual search” brings together three papers (Itti; Heinke, Humphreys, & Tweed; Deco & Zihl) that represent three major approaches to the modelling of visual search and illustrate the power of these approaches in accounting for visual-selection phenomena.

L. Itti (2006 this issue) provides an extension of his saliency-based (simulation) model of attentional allocation by investigating whether an increased realism in the simulations would improve the prediction of where human observers direct their gaze while watching video clips. Simulation realism was achieved by augmenting a basic version of the model with a gaze-contingent foveation filter, or by embedding the video frames within a larger background and shifting them to eye position. Model-predicted salience was determined for locations gazed at by the observers, compared to random locations. The results suggest that emulating the details of visual stimulus processing improves the fit between the model prediction and the gaze behaviour of human observers.

D. Heinke, G. W. Humphreys, and C. L. Tweed (2006 this issue) present an extended version of their “Selective Attention for Identification Model” (SAIM) incorporating a feature extraction mechanism. Heinke et al. show that the revised SAIM can simulate both efficient and inefficient human search as well as search asymmetries, while maintaining translation-invariant object identification. Heinke et al. then turn to the simulation of top-down modulatory effects on search performance reported in recent studies, and they present an experimental test of a novel model prediction. The simulations demonstrate the importance of top-down target expectancies for selection time and accuracy. Also, consistent with the model prediction, a priming experiment with human observers revealed overall RT and search rate effects for valid-prime relative to neutral- and invalid-prime conditions.

A powerful, “neurodynamic model” of the function of attention and memory in visual processing has been developed by G. Deco and his colleagues, based on Desimone and Duncan’s (1995) “biased competition hypothesis”. G. Deco and J. Zihl (2006 this issue) describe the scope of this model, which integrates, within a unifying framework, the explanation of several existing types of experimental data obtained at different levels of investigation. At the microscopic level, single-cell recordings are simulated; at the mesoscopic level of cortical areas, results of fMRI studies are reproduced; and at the macroscopic level, the behavioural performance in psychophysical experiments, such as visual-search tasks, is described by the model. In particular, the model addresses how bottom-up and top-down

(attentional) processes interact in visual processing, with attentional top-down bias guiding the dynamics to focus attention at a given location or on a set of features. Importantly, the modelling suggests that some seemingly serial processes reflect the operation of interacting parallel distributed systems.

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