Visual search and its disorders
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Purpose of review
A greater understanding of the underlying component mechanisms of normal visual search provides explanations for disturbances seen in certain neurological conditions. This review focuses on recent advances in this field which bear on the neurology of visual search in health and disease.

Recent findings
Foremost, visual search requires a normal apparatus for the application of attentional resources to the visual environment and, with that facility lost in hemispatial neglect, search becomes uselessly stuck within one portion of the field. New evidence suggests that loss of normal registration of where the eyes have been compounds the problem. Even if attention can be deployed flexibly, its parameters must be chosen strategically, in terms of saccade amplitude, size of attentional window at each fixation and search path taken. Evidence is growing that the prefrontal cortex plays a complex role in this strategic control. Rehabilitation strategies of the future may be tailored according to which component functions have been lost in different patient groups.

Summary
Visual search is a dominant human activity and provides not only a window into how brain function is deranged after structural damage, but also offers the prospect of an ideal modality through which to deliver future behavioural therapies. New techniques have advanced our understanding of the physiology of visual search enormously in the past few decades. The time is now ripe in which to begin to integrate these findings into our understanding of the pathophysiology and treatment prospects of neurological disorders like hemispatial neglect, hemianopia and other deficits after stroke.

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Introduction
Searching for information in our visual environment is an activity which human beings are engaged in for most of their waking lives. It is a fascinating behaviour to study because it combines what we know about the properties of the human visual system, attentional mechanisms and the control of eye movements.

It is something we have all intuitively observed, and that poker players know well how to exploit, that we are actually quite good at concentrating on aspects outside the direct line of sight, without moving our eyes [1]. At each fixation our maximal discriminatory function (known as acuity) is limited by the density of photo-receptors in the retina, maximal in the part covering the central 4 degrees (foveal vision). Acuity, however, can be significantly enhanced, in any part of the visual field, if we direct our attention towards that area. Attention is a finite resource and devoting it to one or multiple areas, or particular visual features, results in it being less available elsewhere [2]. An understanding of the mechanisms of visual attention and the consequences of its deployment is integral to an understanding of how humans achieve visual search and why its performance is sometimes deranged in neurological disorders.

Exogenous 'capture' and endogenous 'allocation' of covert visual attention
An individual's attention can be 'caught' by features in the environment or it can be 'internally allocated' by the individual based upon his or her current behavioural goals [3,4]. The former is referred to as stimulus-driven or 'exogenous' attention, with the ability of a stimulus to capture attention described as 'salience', and the latter is known as goal-directed or 'endogenous' attention. The combination of these, at any one instant, shapes the way humans search.

The simplest search field, in fact one that does not really require any search at all, is the presence of a single target object in an otherwise blank environment. When the target suddenly appears it immediately captures our attention 'exogenously' and we might, for example, register its appearance by making a manual response, the reaction time of which is a measure of the speed of its detection. The provision of spatial cues, at some time interval in advance of the arrival of the target, has told us a lot about how attention operates. Such experimental manipulations of the locus of attention have proved that attention not only speeds detection of a target, but also improves the quality of visual discriminatory power at

that point in the visual field. That this is not just a shift downwards in the individual's perceptual threshold (criterion) to respond [5–7] has been established by recent studies that followed subjects' speed of response for given levels of accuracy [8,9]. Attention has been shown to increase the sensitivity of the visual system in a range of tasks, including those requiring contrast sensitivity [10–12], texture segmentation [8,9] and visual search [13,14].

Mechanisms of covert visual search

In the real world, targets for visual search exist invariably in the context of other similar, nontarget visual items, called 'distractors'. It is a common observation, however, that some targets naturally stand out, such as a colourful hat in a crowd, or a misaligned picture frame in a gallery. Indeed, like the sudden onset mentioned above, some targets, possessed of certain basic 'features' such as size, orientation, colour or motion, seem to be instantly discernible. The speed with which they exogenously capture attention is independent of the number of accompanying distractor items which lack their defining feature. Their visual salience almost certainly derives from their having visual features which coincide with the response properties to which the receptive fields of cells located at the earlier stages of visual processing are most tuned [15]. They are detected in 'parallel' across the visual field [16].

By contrast, when a target is not easily discriminated from distractors, time taken to search for and detect that target is proportionately influenced by the number of distracting elements present – the 'set size' effect [16]. Gradually lessening, by degree, the feature discriminability of the target progressively increases the set size effect of the search required to detect it, suggesting that set-size independent and highly set-size dependent searches represent opposite ends of a continuum [17–19]. There is little doubt that an increasing set-size effect in search indicates an increasing attentional requirement for that search and an increasing susceptibility to interference from other attentionally demanding tasks [20,21]. What remains controversially debated is whether this extra processing time, with increasing set size, reflects a process of attention visiting serially the location of each putative target item on an early feature map – the simplest explanation [16] – or whether there is no sequential mechanism. In the latter case, the whole field would be processed in parallel during a period of competition between target 'signal' and 'distractor' noise, which would become more protracted the harder the discrimination process and acquire more attentional content because of a greater need for 'top–down' priming, or biasing, of the feature processing units involved [18,22].

If processing of a highly salient feature target represents the simplest instance of operation of a parallel search mechanism, evidence suggests that it is unlikely to occur entirely divorced from endogenous attentional influences. It can be speeded by prior knowledge of target identity [23] or prior allocation of spatial attention [14,24,25] to its upcoming location, suggesting that 'top–down' attentional settings apply.

Interestingly, whilst inclusion of an additional relevant distractor (one varying in the target feature dimension) is more likely to slow search than an irrelevant (cross-dimensional) distractor, it is only perceptual exclusion of the latter which is modulated by cued expectancies of the target feature [26], suggesting that top–down attention may be unable to influence processing within feature maps, but rather comparisons between.

With this in mind, it is a resonant finding that recent experiments, requiring discrimination of low spatial frequencies, demonstrate that the differential benefits and costs of cued attention, at various points across the retina, prevail upon the global and not the local properties of the test stimulus. This implies that attention is acting at the level of 'second-order' (global) feature processing structures [9].

More attentionally demanding types of search also benefit from spatial cuing [25] and repeated practice in looking for the same target [27–29]. In a similar way to how sudden onsets can override endogenous attention in simple attentional paradigms [30,31], in visual search displays placing an irrelevant but highly salient singleton amongst the distractors will always delay target detection, unless both the colour identity of the singleton and that of the target are known in advance [32]. This finding supports the notion that 'top–down' control attentional settings for search are likely to involve both target-enhancing [33] and distractor-inhibiting control [34].

Recent evidence now appears to argue against a serial spatial attentional process in searching for poorly discriminable targets. Whilst spatial cuing attenuates the effect of retinal eccentricity on target detection, it does not overcome the set size effect, suggesting that circumventing the need to visit nontarget locations is not enough to eliminate their influence on the target identification process [14,35]. A recent analysis of the dispersal dynamics of speed-accuracy trade-off profiles for a difficult search suggested that their set-size dependence best fitted with a model of processing which was parallel, but 'capacity-limited', and not serial [36].

Active visual search with eye movements

Of course, normally when humans search they use their eyes, making many precise steps in gaze position known

as saccades. Each movement is preceded by a shift of attention to the goal of the upcoming saccade [37], which at that moment consumes most of the available spatial attentional resources [38]. That searching with eye movements involves a serial attentional process is without argument. Indeed the set size effects on reaction time in covert search tasks are identically paralleled by the number of eye movements made during overt search [39,40]. An area where an understanding is only just starting to emerge is on what exogenous and endogenous factors lead individuals to make the spatiotemporal sequence of saccades which constitute the search path. Here lies the major challenge for research into eye movements during search.

Exogenous visual information on the possible location of the target is only available at the time of fixation. Although we know from covert cuing studies that individuals can focus attention eccentrically, it is likely that for normal, active search, endogenous visual attention is distributed concentrically, radiating out from foveal vision, though, by analogy with what is known from masking studies in reading, it may be biased in the direction of search. What is apparent is that the size of this window, or 'attentional field', is strategically chosen to complement the perceived visual discriminability of the target and that saccades made during search are of an average amplitude which will efficiently bring the attentional field adjacent to coverage provided by the last fixation. Both attentional field size (measured as the effective area over which a target can be detected [41]) and saccade amplitude [42–44] decrease with decreasing target discriminability. It is not known whether, in addition to priming of parallel visual detection processes within that attentional field, there are multiple, additional covert shifts of attention during one fixation, but it is possible such a mechanism might apply to the first fixation at least, the duration of which is consistently proportional to the set size [39,45,46].

If one adopts a broad attentional field for search, making large saccades, the search field is covered faster because spatial attention is more thinly spread. For the gain of speed one trades accuracy, resulting in a larger number of missed target trials, especially if the target is poorly discriminable [47]. To ensure that such targets are not missed, a small attentional field is optimal [48]. This strategy not only slows the search process, but, because so many more fixations are involved, it also risks overburdening one's capacity to hold, on-line, a memory trace for where one has already searched. The way humans minimize the burden on spatial working memory and keep search efficient is to adopt a search path which has overarching systematic form and therefore intrinsic mnemonic value. Typically circular or rectilinear paths are chosen.

Such oculomotor strategy for visual search, however, is not static but is flexibly adjusted as the perceived requirements of the search change, for example if performance feedback indicates that a target has been missed [49].

Impairments of visual search in hemispatial neglect and Balint's syndrome

Given that active visual search is so dependent upon the integration of attentional control with eye movements, it is not surprising that the two neurological conditions which most disrupt visual search are hemispatial neglect, usually resulting from cerebral damage involving the inferior parietal lobule of the right parietal lobe [50], and the much rarer condition, Balint's syndrome, resulting from bilateral parieto-occipital lesions [51].

Patients suffering from hemispatial neglect show an inability to attend to the contralateral half of space, which biases their attention towards the ipsilesional side. On attentional orienting tasks, patients' attention is not captured exogenously by contralateral stimuli, though they can orient when prompted by endogenous cues [52–55]. Whether this insensitivity to exogenous stimuli is secondary to insufficient endogenous allocation to contralateral space in the first place is not known. It was noted early that the attentional deficit impaired a patient's ability to search in contralateral space and this was a sensitive indicator of neglect [56]. In fact a form of search task, involving the patient scoring out targets distributed amongst a complex field of distractors, is now the standard bedside screening test for neglect and provides a quantitative assessment of the severity of the spatial bias [57]. Even with a spatial bias operating, however, one would expect patients to eventually progress, by elimination, into the contralateral field. This does not happen [58–61] (Fig. 1). Recent experiments have established that during such multi-target search, neglect patients are unable to hold on-line a memory trace for where they have searched before, recursively refixating previously fixated targets and reporting these as newly discovered [62]. Search behaviour in hemispatial neglect appears to combine a spatial bias with a loss of trans-saccadic memory for locations previously searched.

It is known that the presence of hemispatial neglect significantly retards patients' recovery from a stroke. Insights provided from the better understanding of mechanisms deficient during visual search may open up a potential treatment path for hemispatial neglect. The neurotransmitter dopamine is strongly implicated in normal spatial working memory and whether future trials of dopamine agonists reveal any ameliorative action in neglect will be eagerly awaited. Effects on visual search have yet to be explored.

Figure 1. Search path in neglect
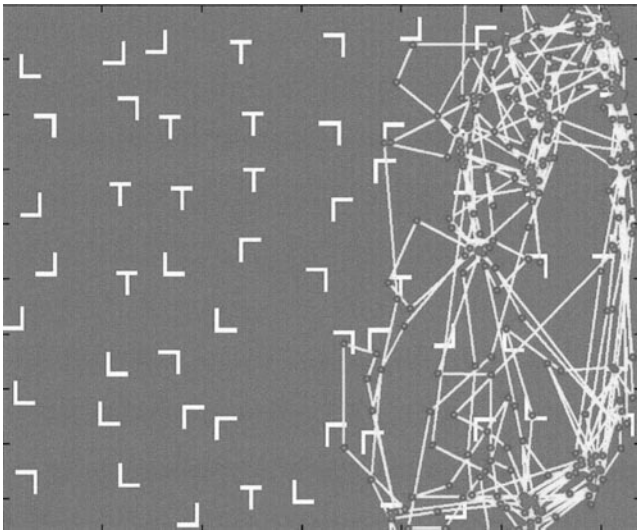
An example of the pattern of saccades made whilst performing a visual search task involving relatively poorly discriminable targets (Ts amongst distractor Ls), in a patient with left hemispatial neglect. The patient fails to explore the left side of the display, and also recursively researches the far right (reproduced with permission from [62]).

In Balint's syndrome the attentional deficits are profound and bilateral [63,64]. Because of the rarity of this syndrome, opportunities to study its pathophysiology have been few, but it potentially offers a very valuable insight into the role of attention in visual processing and conscious perception. Progression of the search path in patients with Balint's syndrome is extremely incremental – infrequent, tiny saccades with long periods of fixation between (Fig. 2). Underlying this is an extremely narrowed attentional field due to an inability to apportion attention to the periphery of vision. Difficulties in target detection may also result from a deficiency of perceptually 'binding', in space, aspects of the target's features sufficient for its identification (simultagnosia) [65–68]. Whether detection of salient targets, in parallel, across the visual field is spared, despite the constricted attentional field, is not clear, preservation being reported in some cases but not in others [49].

Hemianopia and compensation strategy
Though, at each fixation, patients with damage to the visual pathways posterior to the optic chiasm are unable to see, in part or completely, the contralateral visual field (hemianopia), they are nonetheless able to completely search across a visual search field, such as a cancellation task (provided they do not have coexistent hemispatial neglect). The search path is distinguished by frequent exploratory saccades into the blind part of the visual field [60,69,70] (Fig. 3). This distinctive pattern of search provides confirmation that, where normal attentional

Figure 2. Search paths in a patient with Balint's syndrome (due to bilateral occipitoparietal damage)
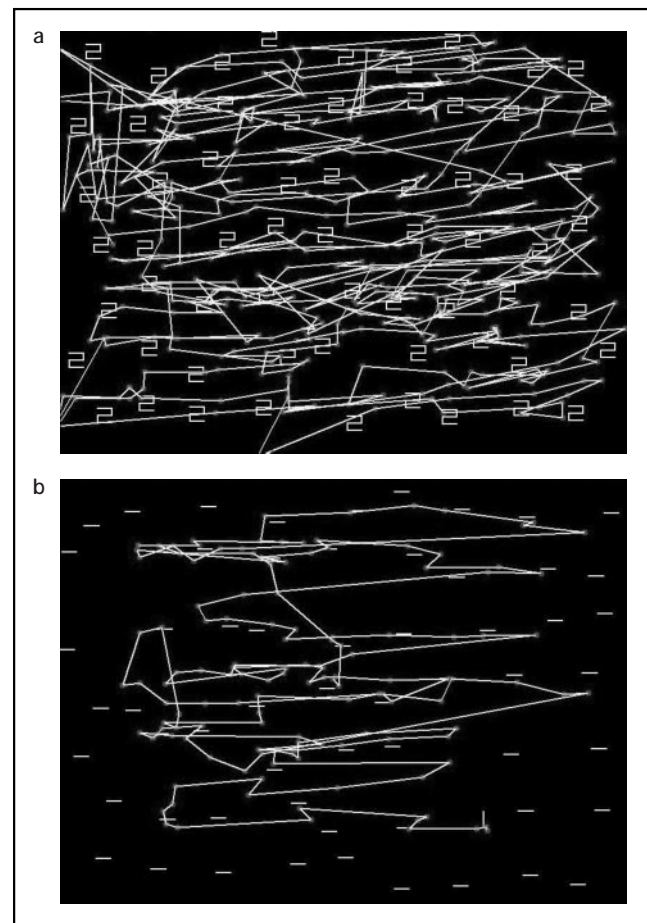

(a) An example of the saccade path taken during a target-absent trial whilst searching for the presence of a single poorly discriminable target (a '5' shape amongst '2'-shaped distractors). The search path is composed of small saccades, slow progression to different areas of the display and very prolonged fixation durations [49]. (b) The same patient as (a), but now searching for a highly discriminable target (vertical line amongst horizontal line distractors). Note that despite the high target salience, the Balint's patient cannot attend to it until it is brought into central vision by serial progression of the search path [49]. Normal people would detect this type of target within a single fixation.

mechanisms are intact, oculomotor strategy can be adjusted to compile a complete picture of the search field, even though each fixation provides an incomplete view [71]. There is some evidence that actively encouraging patients to make this strategic adaptation can speed up their rehabilitation [72,73], but still considerable scope exists for refining the types of therapy used and identifying the patient types most likely to benefit.

Effects of focal cortical lesions
The involvement of posterior parietal and frontal cortical areas in visual search has been demonstrated by

Figure 3. Search path in a patient with left hemianopic field loss
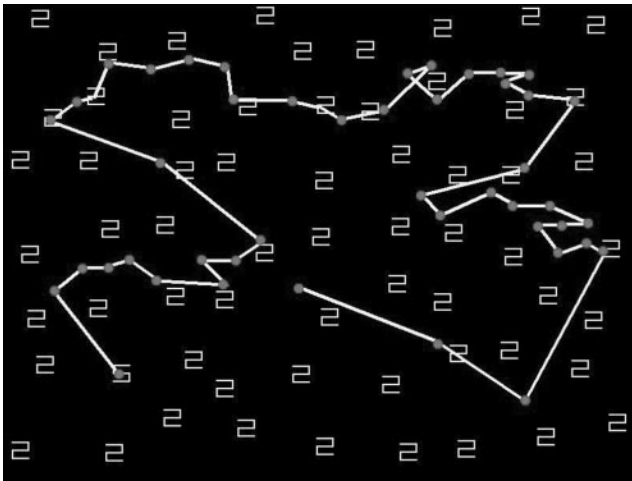
Exploratory saccades are made into the (left) blind field which are of unusually low amplitude (but which generally increase in amplitude as behavioural adaptation to the deficit is learned over time). The hemianopia does not prevent the patient from finding a target situated on the left side of the display.

Figure 4. An example of a disorganized search strategy

This search strategy (searching for a target '5' shape amongst '2'-shaped distractors) was demonstrated by a patient with bilateral orbitofrontal cortical damage (reproduced with permission from [82]). Note the search path shows little systematicity and frequently criss-crosses itself.
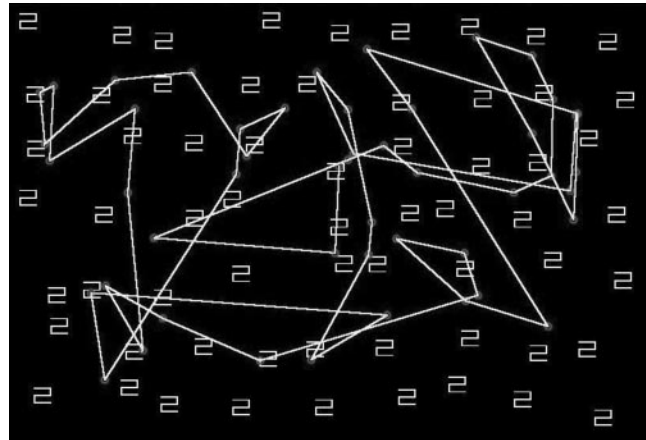
functional imaging studies [74–78]. Much less is known about which areas have roles essential to normal search performance. Indeed, despite the prospect of insight from patients with focal cortical lesions, the few studies of search in these patients (excluding those with hemispatial neglect) have largely not found strong alterations in behaviour [79–81]. This discrepancy between involvement and necessity of cortical areas in search may reflect significant functional reserve and plasticity within the cortical network as a whole. There have, however, been two important recent contributions.

Impaired search strategy, resulting in a disorganized search path, has been associated recently with orbito-frontal cortical damage [82], adding to a previous observation in prefrontal lesion patients [81] that prefrontal cortex may contribute to normal elaboration of search strategy (Fig. 4).

Observations from parietal damage have usually been strongly influenced by coexistent neglect. Transient, focal magnetic disruption of cortical function, however, has linked parietal areas to the detection of relevant targets in search paradigms [83].

Conclusion

Using simple search displays, significant steps have been made in understanding the mechanism of visual search in humans. Functional imaging confirms the involve-ment of a broad frontoparietal cortical network. Oculo-graphic techniques have established that neurological

conditions that disturb normal spatial attention, such as hemispatial neglect, not only impair saccadic exploration during search, but may also impair trans-saccadic memory for previously search locations. Attempts to unravel the role of the prefrontal cortex in visual search and, in particular, its contribution to the strategic control of attentional and oculomotor parameters, is likely to be one of the richest seams for further exploration in this field.

References

1   Helmholtz. Treatise on physiological optics, 3rd ed., vol. III. Southall JPC, editor and translator. Washington, DC: The Optical Society of America; 1925 [originally published 1866].

2   Broadbent D. Perception and communication. London: Pergamon Press; 1958.

3   Jonides J. Towards a model of the mind's eye movement. Can J Psychol 1980; 34:103–112.

4   Posner MI. Orienting of attention. Q J Exp Psychol 1980; 32:3–25.

5   Shaw ML. Division of attention among spatial locations: a fundamental difference between detection of letters and detection of luminance. In: Bouma H, Bouwhuis DG, editors. Attention and performance X. Hillsdale, NJ: Erlbaum; 1984. pp. 109–120.

6   Muller HJ, Findlay JM. Sensitivity and criterion effects in the spatial cuing of visual attention. Percept Psychophys 1987; 42:383–399.

7   Palmer J. Set-size effects in visual search: the effect of attention is independent of the stimulus for simple tasks. Vision Res 1994; 34:1703–1721.

8   Yeshurun Y, Carrasco M. Attention improves or impairs visual performance by enhancing spatial resolution. Nature 1998; 396:72–75.

9   Yeshurun Y, Carrasco M. The locus of attentional effects in texture segmentation. Nat Neurosci 2000; 3:622–627.

10 Carrasco M, Penpeci-Talgar C, Eckstein M. Spatial covert attention increases contrast sensitivity across the CSF: support for signal enhance-ment. Vision Res 2000; 40:1203–1215.

11   Lu ZL, Dosher BA. External noise distinguishes attention mechanisms. Vision Res 1998; 38:1183–1198.

12   Prinzmet al W, Amiri H, Allen K, et al. The phenomenology of attention. Conscious Cogn 1997; 6:372–412.

13   Nakayama K, Mackeben M. Sustained and transient components of focal visual attention. Vision Res 1989; 29:1631–1647.

14   Carrasco M, Yeshurun Y. The contribution of covert attention to the set-size and eccentricity effects in visual search. J Exp Psychol Hum Percept Perform 1998; 24:673–692.

15   Hubel DH, Wiesel TN. Ferrier lecture: functional architecture of macaque monkey visual cortex. Proc R Soc Lond B Biol Sci 1977; 198:1–59.

16   Treisman AM, Gelade G. A feature-integration theory of attention. Cognit Psychol 1980; 12:97–136.

17   Bergen JR, Julesz B. Rapid discrimination of visual patterns. IEEE Trans Systems Man Cybernetics 1983; 13:857–863.

18   Duncan J, Humphreys GW. Visual search and stimulus similarity. Psychol Rev 1989; 96:433–458.

19   Cheal M, Lyon DR. Attention in visual search: multiple search classes. Percept Psychophys 1992; 52:113–138.

20   Braun J, Julesz B. Withdrawing attention at little or no cost: detection and discrimination tasks. Percept Psychophys 1998; 60:1–23.

21   Lee DK, Koch C, Braun J. Spatial vision thresholds in the near absence of attention. Vision Res 1997; 37:2409–2418.

22   Duncan J, Humphreys G, Ward R. Competitive brain activity in visual attention. Curr Opin Neurobiol 1997; 7:255–261.

23   Treisman A. Features and objects: the fourteenth Bartlett memorial lecture. Q J Exp Psychol A 1998; 40:201–237.

24   Morgan MJ, Ward RM, Castet E. Visual search for a tilted target: tests of spatial uncertainty models. Q J Exp Psychol A 1998; 51:347–370.

25   Greenwood PM, Parasuraman R. Scale of attentional focus in visual search. Percept Psychophys 1999; 61:837–859.

26   Muller HJ, Heller D, Ziegler J. Visual search for singleton feature targets within and across feature. Percept Psychophys 1995; 57:1–17.

27   McLeod P, Driver J, Crisp J. Visual search for a conjunction of movement and form is parallel. Nature 1988; 332:154–155.

28   Nakayama K, Silverman GH. Serial and parallel processing of visual feature conjunctions. Nature 1986; 320:264–265.

29   Theeuwes J, Kooi FL. Parallel search for a conjunction of contrast polarity and shape. Vision Res 1994; 34:3013–3016.

30   Muller HJ, Rabbitt PM. Spatial cueing and the relation between the accuracy of 'where' and 'what' decisions in visual search. Q J Exp Psychol A 1989; 41:747–773.

31   Yantis S. Stimulus-driven attentional capture and attentional control settings. J Exp Psychol Hum Percept Perform 1993; 19:676–681.

32   Theeuwes J, Burger R. Attentional control during visual search: the effect of irrelevant singletons. J Exp Psychol Hum Percept Perform 1998; 24:1342–1353.

33   Wolfe JM. Guided search 2.0: a revised model of visual search. Psychonom Bull Rev 1994; 1:202–238.

34   Treisman A, Sato S. Conjunction search revisited. J Exp Psychol Hum Percept Perform 1990; 16:459–478.

35   Wolfe JM, O'Neill P, Bennett SC. Why are there eccentricity effects in visual search? Visual and attentional hypotheses. Percept Psychophys 1998; 60:140–156.

36   McElree B, Carrasco M. The temporal dynamics of visual search: evidence for parallel processing in feature and conjunction searches. J Exp Psychol Hum Percept Perform 1999; 25:1517–1539.

37   Hoffman JE, Subramaniam B. The role of visual attention in saccadic eye movements. Percept Psychophys 1995; 57:787–795.

38   Kowler E, Anderson E, Dosher B, Blaser E. The role of attention in the programming of saccades. Vision Res 1995; 35:1897–1916.

39   Zelinsky GJ, Sheinberg DL. Eye movements during parallel-serial visual search. J Exp Psychol Hum Percept Perform 1997; 23:244–262.

40   Williams DE, Reingold EM, Moscovitch M, Behrmann M. Patterns of eye movements during parallel and serial visual search tasks. Can J Exp Psychol 1997; 51:151–164.

41   Jacobs AM. On the role of blank spaces for eye-movement control in visual search. Percept Psychophys 1987; 41:473–479.

42   Prinz W, Kehrer L. Recording detection distances in continuous search. In: Groner R, Fraisse P, editors. Cognition & eye movements. Amsterdam: North-Holland; 1982. pp. 48–56.

43   Rayner K, Fisher DL. Eye movements and perceptual span during visual search. In: O'Regan JK, Levy-Schoen A, editors. Eye movements: from physiology to cognition. Elsevier; 1987.

44   Jacobs AM. Eye movement control in visual search: how direct is visual span control? Percept Psychophys 1986; 39:47–58.

45   Findlay JM. Global visual processing for saccadic eye movements. Vision Res 1982; 22:1033–1045.

46   Findlay JM. Saccade target selection during visual search. Vision Res 1997; 37:617–631.

47   Prinz W. Attention and sensitivity in visual search. Psychol Res 1984; 45:355–366.

48   Kraiss KF, Knaeuper A. Using visual lobe area measurements to predict visual search performance. Hum Factors 1982; 24:673–682.

49   Mort DJ, Mannan SK, Anderson EA, et al. Continuous range of oculomotor strategy during visual search in normal adults and its adaptability [abstract]. J Neuro-ophthalmol 2001; 25:14.

50   Vallar G. Extrapersonal visual unilateral spatial neglect and its neuroanatomy. Neuroimage 2001; 14:S52–S58.

51   Husain M, Stein J. Rezso Balint and his most celebrated case. Arch Neurol 1988; 45:89–93.

52   Posner MI, Walker JA, Friedrich FJ, Rafal RD. Effects of parietal injury on covert orienting of attention. J Neurosci 1984; 4:1863–1874.

53   Morrow LA, Ratcliff G. The disengagement of covert attention and the neglect syndrome. Psychobiology 1988; 16:261–269.

54   Friedrich FJ, Egly R, Rafal RD, Beck D. Spatial attention deficits in humans: a comparison of superior parietal and temporal-parietal junction lesions. Neuropsychology 1998; 12:193–207.

55   Bartolomeo P, Sieroff E, Decaix C, Chokron S. Modulating the attentional bias in unilateral neglect: the effects of the strategic set. Exp Brain Res 2001; 137:432–444.

56   Chedru F, Leblanc M, Lhermitte F. Visual searching in normal and brain-damaged subjects: contribution to the study of unilateral inattention. Cortex 1973; 9:94–111.

57   Mesulam M-M. Principles of behavioural neurology: tests of directed attention and memory. Philadelphia: Davis; 1985.

58   Pavlovskaya M, Ring H, Groswasser Z, Hochstein S. Searching with unilateral neglect. J Cogn Neurosci 2002; 14:745–756.

59   Samuelsson H, Hjelmquist EK, Jensen C, Blomstrand C. Search pattern in a verbally reported visual scanning test in patients showing spatial neglect. J Int Neuropsychol Soc 2002; 8:382–394.

60   Behrmann M, Watt S, Black SE, Barton JJ. Impaired visual search in patients with unilateral neglect: an oculographic analysis. Neuropsychologia 1997; 35:1445–1458.

61   Harvey M, Olk B, Muir K, Gilchrist ID. Manual responses and saccades in chronic and recovered hemispatial neglect: a study using visual search. Neuropsychologia 2002; 40:705–717.

62   Husain M, Mannan S, Hodgson T, et al. Impaired spatial working memory across saccades contributes to abnormal search in parietal neglect. Brain 2001; 124:941–952.

63   Rapcsak SZ, Cimino CR, Heilman KM. Altitudinal neglect. Neurology 1988; 38:277–281.

64   Verfaellie M, Rapcsak SZ, Heilman KM. Impaired shifting of attention in Balint's syndrome. Brain Cogn 1990; 12:195–204.

65   Kerkhoff G, Heldmann B. Balint syndrome and associated disorders: anamnesis–diagnosis–approaches to treatment. Nervenarzt 1999; 70:859–869.

66   Friedman-Hill SR, Robertson LC, Treisman A. Parietal contributions to visual feature binding: evidence from a patient with bilateral lesions. Science 1995; 269:853–855.

67   Rizzo M, Vecera SP. Psychoanatomical substrates of Balint's syndrome. J Neurol Neurosurg Psychiatry 2002; 72:162–178.

68   Kim MS, Robertson LC. Implicit representations of space after bilateral parietal lobe damage. J Cogn Neurosci 2001; 13:1080–1087.

69   Zihl J. Visual scanning behavior in patients with homonymous hemianopia. Neuropsychologia 1995; 33:287–303.

70 Meienberg O, Zangemeister WH, Rosenberg M, *et al.* Saccadic eye movement strategies in patients with homonymous hemianopia. Ann Neurol 1981; 9:537–544.

71 Zangemeister WH, Oechsner U, Freksa C. Short-term adaptation of eye movements in patients with visual hemifield defects indicates high level control of human scanpath. Optom Vis Sci 1995; 72:467–477.

72 Kerkhoff G, Munssinger U, Meier EK. Neurovisual rehabilitation in cerebral blindness. Arch Neurol 1994; 51:474–481.

73 Pambakian AL, Wooding DS, Patel N, *et al.* Scanning the visual world: a study of patients with homonymous hemianopia. J Neurol Neurosurg Psychiatry 2000; 69:751–759.

74 Gitelman DR, Parrish TB, Friston KJ, Mesulam MM. Functional anatomy of visual search: regional segregations within the frontal eye fields and effective connectivity of the superior colliculus. Neuroimage 2002; 15:970–982.

75 Donner T, Kettermann A, Diesch E, *et al.* Involvement of the human frontal eye field and multiple parietal areas in covert visual selection during conjunction search. Eur J Neurosci 2000; 12:3407–3414.

76 Leonards U, Sunaert S, Van Hecke P, Orban GA. Attention mechanisms in visual search: an fMRI study. J Cogn Neurosci 2000; 12 (Suppl 2):61–75.

77 Donner TH, Kettermann A, Diesch E, *et al.* Visual feature and conjunction searches of equal difficulty engage only partially overlapping frontoparietal networks. Neuroimage 2002; 15:16–25.

78 Wilkinson DT, Halligan PW, Henson RN, Dolan RJ. The effects of interdistracter similarity on search processes in superior parietal cortex. Neuroimage 2002; 15:611–619.

79 Hildebrandt H, Giesselmann H, Sachsenheimer W. Visual search and visual target detection in patients with infarctions of the left or right posterior or the right middle brain artery. J Clin Exp Neuropsychol 1999; 21:94–107.

80 Karatekin C, Lazareff JA, Asarnow RF. Parallel and serial search in two teenagers with lesions of the mesial parietal cortex. Neuropsychologia 1999; 37:1461–1468.

81 Zihl J, Hebel N. Patterns of oculomotor scanning in patients with unilateral posterior parietal or frontal lobe damage. Neuropsychologia 1997; 35:893–906.

82 Hodgson T, Mort D, Chamberlain M, *et al.* Orbitofrontal cortex mediates inhibition of return. Neuropsychologia 2002; 40:1891–1901.

83 Ashbridge E, Walsh V, Cowey A. Temporal aspects of visual search studied by transcranial magnetic stimulation. Neuropsychologia 1997; 35:1121–1131.