

The integration of parallel and serial processing mechanisms in visual search: evidence from eye movement recording

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Abstract

We examined timing and scanning paths of eye movements during a visual search task, in which subjects had to detect, as quickly as possible, the presence or absence of a target among distractors [Q-like element among O stimuli (QvsO) and vice-versa (OvsQ)]. According to an influential theory [Treisman, A. & Gelade, G. (1980) *Cognitive Psychol*, **12**, 97–136; Treisman, A. & Sato, S. (1990) *J. Exp. Psychol. Hum. Percept. Perform.*, **16**, 459–478], only tasks yielding nonflat search functions (OvsQ) involve focal attention. Alternative models propose that all kinds of visual search are resolved by a biased competitive process, working in parallel across the visual field. Data show that QvsO and OvsQ tasks are characterized by quantitative rather than by qualitative differences in search strategy. No differences between the two tasks were found regarding either the percentage of saccades foveating single stimulus items or the timing of the button response with respect to the onset of the last foveation saccade within a trial. Furthermore, the number of saccades made during search predicted very accurately the time required to accomplish the task and fixation times were independent of the number of stimulus items. On the basis of our results there is no reason to postulate the occurrence of shifts of visuospatial attention, other than those associated with the executions of saccadic eye movements, which are driven by a parallel feature analysis of the visual scene, in both types of search tasks. A time-limited competitive model for attentive target identification, in which both parallel (competitive) and serial (attentive) processing mechanisms are integrated, can account for these findings, providing a unified conceptual framework for all kinds of visual search.

Introduction

How the brain selects an object of interest in a natural visual scene is a debated and still unsolved issue. According to an influential theory (Treisman & Gelade, 1980; Treisman & Sato, 1990), neural processing underlying visual search is largely determined by the feature complexity which defines the target with respect to the other irrelevant visual elements. This view predicts that a serial shift of visuospatial attention, whereof search is performed through a sequential examination of each item in turn, is always required, except when targets are defined by just one elementary feature. An alternative model (Duncan & Humphreys, 1989; Duncan *et al.*, 1997) proposes that all kinds of search tasks can be solved by a biased competitive mechanism, which works in parallel across the visual field, without necessarily consuming attentive resources.

The controversy between 'serial' and 'parallel' theories on visual search stems from the different perspectives which various authors have taken in order to explain nonflat search functions, i.e. the linear increasing of target detection times as a function of the number of items present in the visual scene. According to the 'feature integration theory' of Treisman and coworkers, 'easy' search tasks (target differing from distractors by just one elementary feature) are

accomplished 'preattentively', and the detection times are independent of the number of items in the visual scene. By contrast, in tasks yielding nonflat search functions (e.g. in a conjunction search, in which targets are defined by a combination of features), visual search is assumed to be a self-terminating process. The scrutiny of individual visual objects is carried on until 50% of the array elements, on the average, has been serially processed, after being focused by spatial attention. From the alternative viewpoint of parallel models, the visual search process is qualitatively similar for all kinds of tasks. Target selection results from a mutual inhibitory competitive interaction among neuronal populations activated by various features of the array elements (feature maps). The time taken by top-down biasing influences (e.g. memorized target template) to resolve the competition in favour of the searched visual object would then depend, in a graded manner, on the signal-to-noise ratio between the prespecified target and its visual environment (Duncan & Humphreys, 1989). A widely used class of visual search paradigms consists of the so-called asymmetry tasks (Beck, 1973; Treisman & Souther, 1985). These paradigms yield either flat or nonflat search functions, depending on which item in a stimulus pair is designated as target or distractor, i.e. by reversing the target-distractor assignment in the stimulus array (see Fig. 1).

Relatively few studies in the literature have addressed the oculomotor behaviour during visual search tasks in human subjects

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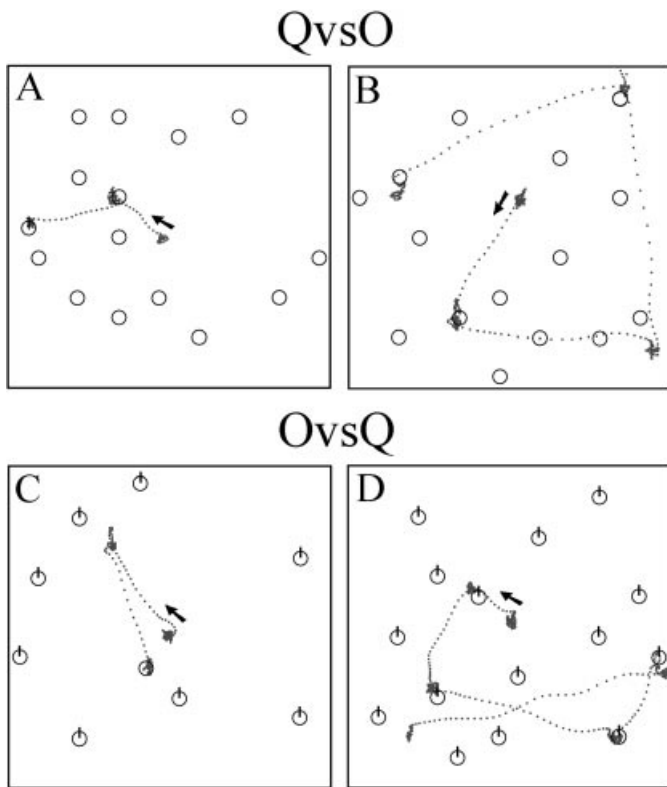


FIG. 1. Examples of eye movements paths (dots) during (A and B) QvsO and (C and D) OvsQ search tasks, in both target-present (A and C) and target-absent (B and D) trials. Search paths are shown between stimulus onset and time at which subject pressed the response button. Arrows indicate beginning and direction of eye movement traces.

(Zelinsky, 1996; Findlay, 1997; Zelinsky & Sheinberg, 1997; Gilchrist *et al.*, 1999). In the present work, we have investigated the timing and scanning paths of eye movements during an asymmetry visual search task. We provide evidence that both a serial shift of focal attention and a parallel feature analysis across the visual field are essential stages for all kinds of visual search tasks. A hybrid, unified model of search strategy, which does not entail the dichotomy between 'attentive' and 'preattentive' types of visual search, can fully account for the present findings.

Materials and methods

Subjects

Six neurologically normal volunteer subjects (four female and two male, age 22–30 years) participated in the study. Written informed consent was obtained from all subjects. This study was conducted under protocols approved by local ethics committee.

Procedure

We recorded eye movements while the subjects were instructed to indicate as rapidly as possible, by pressing two alternative buttons on a response pad, whether a target stimulus was present or absent in an array of distractors. No specific instructions about eye movements were given to the subjects, except to fixate at the beginning of each trial a central cross, which disappeared at stimulus presentation. A few trials for each stimulus condition were presented at the beginning of the session in order to familiarize the subjects with the task.

In a second series of experiments, five subjects (already tested with the previous protocol) were investigated with the same series of search arrays, but after being instructed to avoid the execution of eye movements by fixating a central cross, which was maintained visible throughout the visual search period. In this case too, subjects were allowed to get acquainted with the task by practicing for a few trials before starting the recording session.

In all experimental conditions trials were response-terminated, that is, the search array was kept visible on the screen up until a response button was pressed by the subject. At button press the search array was removed and the central fixation cross was redisplayed.

Stimuli

Two search conditions were investigated, in which O and Q-like stimuli were used as target and distractor elements and vice versa. These stimuli are well known to constitute an asymmetry paradigm, in which the search for a O target embedded in a field of Q-like distractors (OvsQ) yields nonflat search functions. In the reversed condition (looking for a Q-like target among O elements, QvsO), response times become independent of the number of distractors. Stimuli were composed of a variable number of items (3, 9 or 15, including target), randomly distributed over an area covering a visual angle of $\pm 20^\circ$. The OvsQ and QvsO stimulus arrays were perfectly balanced, by exactly matching the spatial location of target and distractors in the two search conditions. Furthermore, the location of the target was evenly distributed among three possible eccentricities, at 6, 12 and 18°. For each eccentricity, target could occur at one of 12 possible positions on an ideal circumference, evenly spaced at 30° intervals. Each stimulus element subtended a visual angle of 1.83° . Stimuli were rear-projected on a wide-tangent screen placed 1.5 m in front of the subject. An experimental session comprised 72 trials for each stimulus condition, target-absent and target-present trials being randomly intermixed in equal proportions.

Recording apparatus

Horizontal and vertical eye movements were recorded by means of DC-electrooculography (0–200 Hz bandpass-filtered). Ag–AgCl electrodes were placed at the external canthi and above and below the right eye. Electrooculogram (EOG) signals were logged at 500 samples/s. EOG calibration was frequently repeated during the experimental session and drift of DC offset was compensated within each trial by making the subject fixate a central cross before stimulus onset. The subject's head was steadied using a combination chin-rest and head-support device.

Statistical analysis

Statistical data analysis and significance tests were performed by using S-PLUS 2000 Professional for Windows (MathSoft, Inc.). In particular, the analysis of the intersaccadic latencies and of the latencies of the first saccade with respect to the stimulus onset were made after a statistical modelling of the data by means of Generalized Linear Models (McCullagh & Nelder, 1989). This technique provides a way to estimate the mean response as a linear function of the values of some set of continuous and/or categorical predictors, by means of a nonlinear iterative procedure. In our case, mean saccadic latency was estimated as a Poisson regression of the number of stimulus items, experimental subjects and type of saccadic movement (ordinal number of the saccade in a search sequence or occurrence of target foveation; see Results for details). The dependency of saccadic latency on the various predictors was estimated by testing the statistical significance of the corresponding regression coefficients.

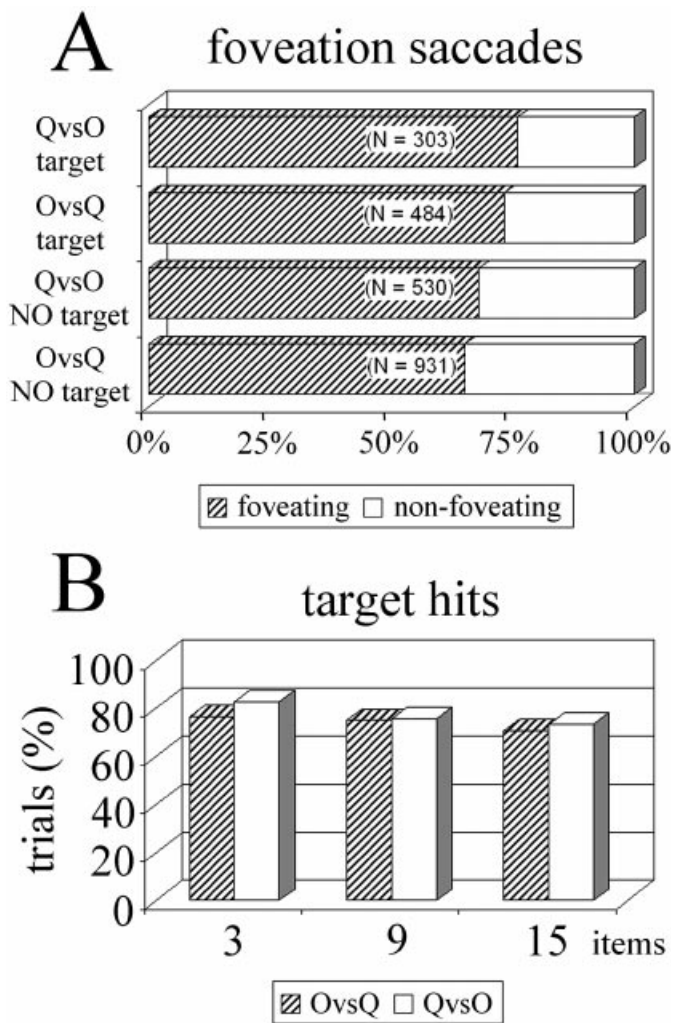


FIG. 2. (A). Bar graph depicting the mean percentage of foveation saccades, i.e. ending on a stimulus item (target or distractor), in QvsO and OvsQ search tasks for target-present and target-absent trials. Eye movements were considered foveation saccades when they ended within a circular area corresponding to twice the diameter of the stimulus item. (B) Mean percentage of target-present trials in which subjects made a foveation saccade onto the target stimulus before pressing the response button, as a function of the number of items. Note that for all the considered parameters, QvsO and OvsQ search conditions did not show any statistically significant difference.

Results

Saccadic occurrence during visual search

Figure 1 shows representative examples of eye movement paths for both OvsQ and QvsO tasks, in target-present (A and C) and target-absent (B and D) trials. It can be clearly seen that saccades are present in all kinds of visual search. By considering all experiments from all subjects, one to several saccades were recorded during the search tasks in 99.8% ($n = 424$) of OvsQ trials and in 98.2% ($n = 434$) of QvsO trials. There is ample evidence that a shift of visuospatial attention is normally linked to the saccadic target location (Deubel & Schneider, 1996; Shepherd *et al.*, 1986; Henderson, 1992; Kowler *et al.*, 1995). Such attention-saccade coupling becomes compelling when the eye movement lands precisely on an individual stimulus item, i.e. when it can be considered a foveation saccade. We arbitrarily classified eye movements as foveation saccades when they

ended within a circular area, around a target or distractor, whose diameter was twice that of the stimulus element. Under this assumption, 67.8% of eye movements in OvsQ trials ($n = 1415$) and 70.8% in QvsO trials ($n = 833$) were classified as foveation saccades. The bar graph of Fig. 2A depicts the mean percentage of foveation saccades for all types of search tasks. A slightly lower occurrence of foveation saccades can be observed in target-absent (66.1%) than in target-present trials (74.2%). However this decrease was almost identical in both QvsO and OvsQ stimulus conditions. In addition, target-present search tasks ended with a foveation saccade onto the target stimulus, before the response button was pressed, in 74.1% of the OvsQ trials ($n = 216$) and in 77.4% of QvsO trials ($n = 212$). Figure 2B shows the mean percentage across subjects of target-hit trials as a function of array size. From the analysis of the results it turned out that, just as for the percentage of foveating saccades, the difference in the percentage of target-hit trials between QvsO and OvsQ search conditions was also far from significance in all subjects. It can thus be concluded that shifts of focal attention are very common events also in tasks characterized by a flat search function, which are generally believed to be carried out by means of preattentive parallel processing.

A possible interpretation for the presence of foveation saccades in QvsO trials is that shifts of focal attention may actually occur only at the end of the search, after the target has been already identified in the stimulus array by means of 'preattentive' parallel mechanisms. According to this hypothesis, an attentive engagement would be linked just to the final acquisition of a conscious visual experience about the target, or to the guidance of a deliberate motor behaviour (e.g. pressing the response button) taking place after the completion of the target selection process. The data, however, seem to exclude such a possibility. Histograms in Fig. 3 show the distribution of trials with respect to the number of saccades performed during the search, grouped according to the number of items in the stimulus array. It is clear that, as far as the number of saccades, the difference in search strategy between tasks with flat and nonflat search is quantitative rather than qualitative. In particular, it should be noted that two or more saccades are also often required for target detection in the so-called preattentive task (QvsO). This behaviour is even more evident in the target-absent condition, in which the large majority of trials were accomplished with 2–6 saccades. Thus, saccades appear to be part of a precise search strategy, rather than being an 'epiphenomenon' which follows the target identification process. Conversely, a considerable number of OvsQ target-present trials (commonly considered attentive serial search tasks) are successfully accomplished with only one saccadic movement just as in the QvsO condition, even in presence of large stimulus arrays. This finding also points towards the view of a common saccadic strategy in visual search, in which the average number of performed saccades depends on the ease of target detection from the background. The hypothesis of a tight relationship between saccadic behaviour and target detection processes in visual search is also supported by a strong correlation between search response times (RT) and number of saccades. This point is readily demonstrated in Fig. 4, where the mean number of saccades and RTs across all subjects are reported as a function of the number of stimulus items, for both search conditions. As expected, RTs increase with the number of items only in the OvsQ condition, whereas in the reversed task a statistically significant increase of RTs occurs only for target-absent trials. Interestingly, the mean number of saccades shows a very similar behaviour, so that the number of saccadic eye movements made during the search can be taken as a very good predictor of the time required to accomplish the task. In fact, RT and number of

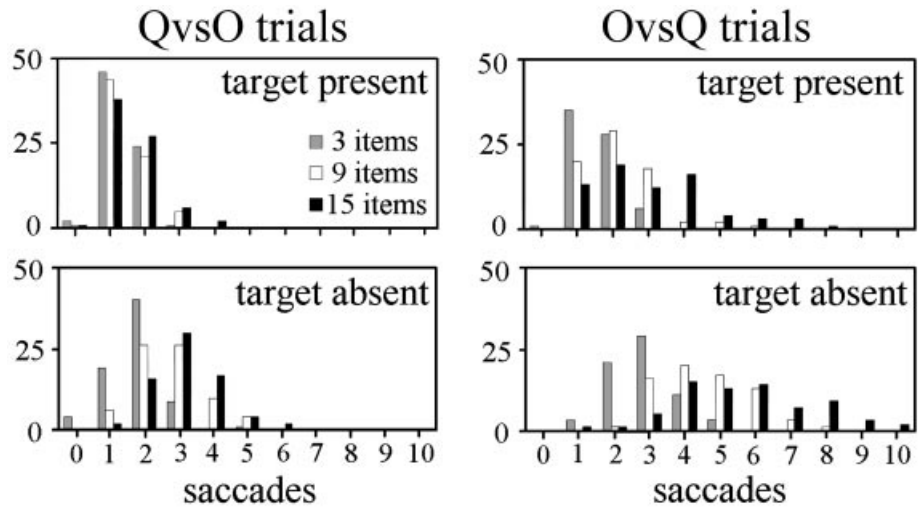


FIG. 3. Distribution histograms of trials as a function of the number of saccades made during visual search and the number of stimulus items (coded with different grey levels), for all task conditions. Data demonstrate that, regarding saccadic behaviour, QvsO and OvsQ conditions are characterized by more quantitative rather than qualitative differences in search strategy.

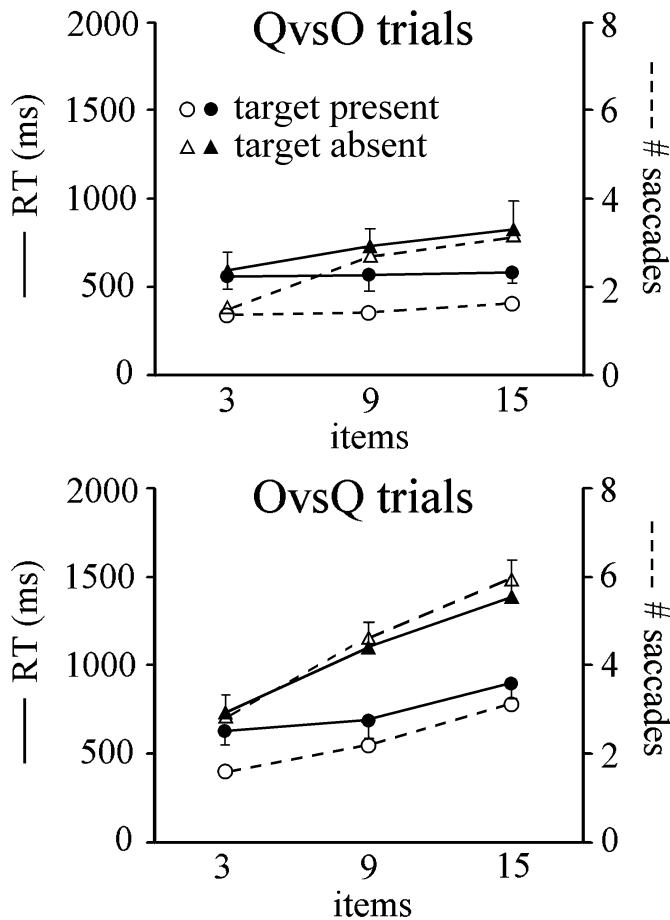


FIG. 4. Mean reaction times (RT, solid lines) and mean number of saccades (dashed lines) as a function of the number of items in the search array, measured across all subjects and experiments, in both QvsO (upper graph) and OvsQ (lower graph) conditions. Dots and triangles represents target-present and target-absent trials, respectively.

saccades resulted to be strongly correlated variables in all search conditions ($r = 0.831$; $P < 0.01$). The prediction of the search time on the basis of the number of saccades becomes strikingly accurate when we take into account the mean RTs, after binning according to

the number of saccades made during the trial. In this case, the coefficients of correlation were 0.994 and 0.889 for the OvsQ and QvsO search conditions, respectively.

Analysis of saccadic latencies

The hypothesis of a unified search strategy may be unwarranted if what differentiates the two search tasks is not the number of saccades, but rather what happens in the intersaccadic intervals. For instance, it may very well be that, in tasks with nonflat search functions, a larger number of covert shifts of visuospatial attention, i.e. displacements of the attentive focus to a different area of the visual field in the absence of eye movements execution (Posner, 1980), is occurring in the time intervals between saccades. If this were true, one should expect longer intersaccadic intervals in those tasks requiring more attentive resources and, possibly, a correlation between the duration of these time intervals and the number of stimulus items. None of these predictions are, however, supported by the experimental data. The bar graphs in the upper panels of Fig. 5 depict the length of the intersaccadic intervals as a function of the number of stimulus items and of the ordinal number of the saccades performed during search. Clearly, fixation times before the first three saccades of each trial, are independent of the number of distractors and are basically identical for QvsO and OvsQ conditions (Generalized Linear Model; $P > 0.1$). The mean \pm SD intersaccadic intervals across subjects in the QvsO task were (in ms) 207 ± 76 , $n = 423$, 186 ± 71 , $n = 291$ and 186 ± 48 , $n = 130$ for the first, second and third intersaccadic intervals, respectively. In the OvsQ search condition, the corresponding mean values were 188 ± 55 , $n = 429$, 182 ± 68 , $n = 364$ and 197 ± 53 , $n = 269$.

The lower panels in Fig. 5 allow a closer analysis of the latency of the first saccade from stimulus onset. Here the first saccadic delay is contrasted for trials in which the eye movement landed ('on-target') or did not land on target ('off-target'). The third group of columns refers to trials in which target was absent ('no-target'). In the OvsQ search condition, latency of the first saccade was statistically independent of the number of distractors ($P > 0.1$), for all three groups. By contrast, in the QvsO task, a mild positive trend was found only for 'on-target' trials ($P = 0.05$). The independency of saccadic latency from the number of distractors for 'on-target' OvsQ trials is a particularly striking result. In fact, serial models predict that, in this case, search should be performed by means of a sequential examination of each item in turn, yielding longer latencies in

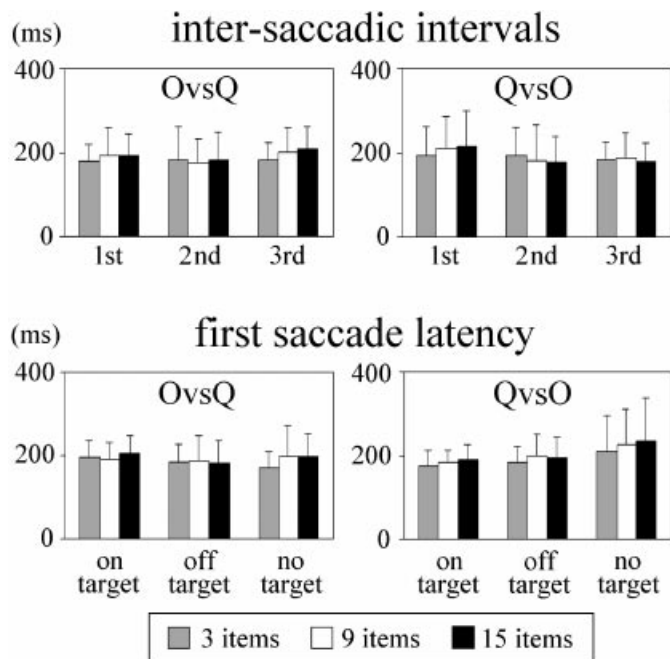


FIG. 5. Upper panels: mean intersaccadic intervals as a function of the ordinal number of the saccades performed during the search task and of the number of stimulus items, for QvsO and OvsQ conditions. The first group of columns represents the mean latency between stimulus onset and the first saccadic eye movement. The second and third groups of columns represent the mean time intervals between the corresponding saccade and the previous one. Lower panels: mean latencies of the first saccade from stimulus onset for QvsO and OvsQ search conditions. The first two groups of columns refer to trials in which the first saccade lands or does not land on target, respectively. The last group of columns refers to target-absent trials. For all columns, the number of stimulus items is coded by different grey levels and upwards line segments indicate standard deviations. Note that both intersaccadic intervals and first saccade latencies are largely independent of the number of stimulus items and of the type of search condition.

response to larger stimulus arrays. Furthermore, first saccade mean latency was very similar in OvsQ and QvsO trials ($P > 0.05$). In particular, the mean values for 'on-target', 'off-target' and 'no-target' groups in the OvsQ condition were (in ms) 197 ± 40 , $n = 66$, 184 ± 53 , $n = 146$ and 188 ± 58 , $n = 216$, respectively. Conversely, in the QvsO condition, the corresponding values were 189 ± 55 , $n = 118$, 192 ± 47 , $n = 89$ and 224 ± 91 , $n = 210$. Once again, particularly interesting is the finding that, even for 'on-target' trials, in which search was completed with just one eye movement, no statistical difference in the first saccade latency could be measured between OvsQ and QvsO conditions. It should also be noted that, in all search tasks, the mean intersaccadic interval is strikingly short, close to the minimum gap allowed by the saccadic control system. In conclusion, these results strongly suggest that a parallel processing of the visual scene is taking place within the time intervals between saccades. In this respect, no indications of a different visual processing mechanism could be found between QvsO and OvsQ search conditions. The result of this parallel process is the selection of a new visual element for a shift of focal attention.

Another strong piece of evidence, in favour of the view that the engagement of focal attention is a normal component of the target detection strategy, even in tasks with flat search functions, comes from the analysis of the time interval between onset of the last saccade within a search trial and button response time. Considering only the trials ($\approx 75\%$) in which subjects made a foveation saccade

onto the target before pressing the button, we are faced with two alternative possibilities: (i) decision about target detection has already been achieved and therefore finger motor response is expected to occur within a short time with respect to saccade onset; (ii) foveation saccade just represents a shift of focal attention towards a candidate target, which still needs to be fully analysed, before a final decision can be made. In this case, button response should be noticeably delayed by a further visual processing time. Experimental data decidedly support this latter hypothesis. In fact, response button was pressed after an average delay of 294 ± 95 and 320 ± 107 ms, with respect to the last saccade onset, in QvsO and OvsQ trials, respectively. Interestingly, this delay was considerably longer in trials accomplished with just one foveation saccade than in trials with two or more saccades. In particular, single saccade trials presented a mean delay of 316 ± 74 , $n = 110$, and of 354 ± 80 ms, $n = 62$ for QvsO and OvsQ tasks, respectively. In multiple saccade trials the corresponding delays were 250 ± 114 , $n = 55$ and 295 ± 109 ms, $n = 100$.

Visual search without eye movements

The reasoning followed so far could raise a fundamental criticism. One could surmise that the area of the visual field within which a target can be detected in a single fixation (the so called 'visual lobe') is smaller than the area covered by the search array. Therefore, a saccadic scanning of the stimulus area would be required in order to improve the low discrimination performance associated with the most eccentric parts of the visual field. If so, our experimental paradigm would force a multiple-fixation visual search irrespective of the target-distractor pairs used as stimuli. The observed similarity in the search strategy would then be dictated by a problem of discrimination accuracy, independently of the 'attentive' or 'preattentive' type of visual processing utilized for target detection.

It should be noted that this interpretation of the data could hardly explain why the average number of saccades required for target detection is consistently lower in the QvsO condition than in the OvsQ one. Actually, if saccades were executed just to improve the discrimination accuracy in the most peripheral parts of the stimulus array, a similar mean number of gaze shifts should be observed in the two search conditions. At most, a larger number of saccades is expected in target-absent trials than in target-present trials, because in the latter ones search should self-terminate at target detection. Nevertheless, in order to demonstrate that (i) target discrimination in our experimental paradigm does not necessarily require a saccadic scanning of the stimulus area and (ii) the freedom of making eye movements produces very similar response times to those observed in search tasks in which eye movements are forbidden, we studied visual search performance after saccades were prevented by asking to the subjects to fixate a central cross during the whole search time period.

Despite all subjects reporting a strong urge to make saccades, all of them were reasonably successful at maintaining fixation throughout the search task. Only 9.3% of QvsO trials and 5.3% of OvsQ trials showed a saccadic contamination and therefore were excluded from any further analysis. Response accuracy was also largely preserved. Figure 6 compares the mean percentage of incorrect responses between fixation and eye-movement experiments as a function of target eccentricity. It can be clearly seen that the occurrence of erroneous target identifications is in general very low. In addition, fixation increases the error percentage exclusively at the highest target eccentricity. However, it should be stressed that 90% of the incorrect responses were false positive, making it very unlikely that errors were mainly due to problems in discrimination performance. In

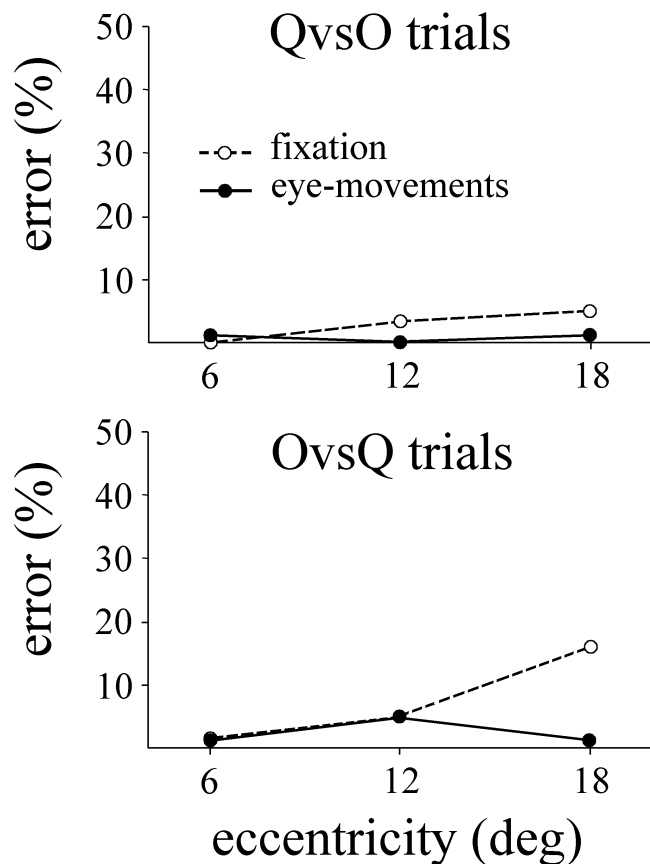


FIG. 6. Mean percentage of incorrect responses, as a function of target eccentricity, for QvsO and OvsQ search tasks. Circles represent trials in which subjects had to fixate a central cross throughout the search time period. Dots represent trials with active visual search, in which eye movements were allowed. Error occurrence is in general very low and fixation slightly increases the error percentage exclusively at the highest target eccentricity.

fact, one would expect that a poor discrimination of most eccentric targets would have induced mostly an increase of false negative responses. Therefore, the decrease in response accuracy can possibly be ascribed to the fact that subjects had to perform a more demanding double-task paradigm, in which target discrimination had to be accomplished together with a voluntary suppression of saccadic eye movements.

In summary, we have demonstrated that the execution of saccades is not strictly necessary in order to successfully perform our visual search paradigm, implying that the observed eye movement pattern directly results from and faithfully reflects the search strategy underlying the visual processing of the stimulus array. Furthermore, in most subjects, also manual RTs for target detection are essentially the same, irrespective of the presence or absence of a saccadic scan of the search area. Figure 7 compares the average RTs measured in trials in which eye movements were permitted (continuous lines) or forbidden (dashed lines), as a function of the number of items in the search array. In this respect subjects could be neatly divided in two groups, extremely homogenous as far as the effects of fixation on RTs. In three subjects (upper panels), RTs were basically identical for all array sizes, except for target-absent OvsQ trials, in which fixation resulted in considerably shorter response times. In the other two subjects (lower panels), fixation induced an increase of RTs for all

stimulus conditions, which amounted on the average to 37.2% of the value measured during the eye movement trials. In all cases, however, the presence or absence of eye movements did not affect the flat or nonflat behaviour of search functions, depending on the target-distractor pairs used as a stimulus.

Discussion

Given that the exploration of the visual scene with eye movements is certainly a natural and spontaneous component of any visual search, it is surprising that relatively few studies in the literature investigated the use and the functional relevance of oculomotor behaviour during this kind of task (Zelinsky, 1996; Findlay, 1997; Zelinsky & Sheinberg, 1997; Motter & Belky, 1998a, b; Gilchrist *et al.*, 1999). In most investigations, eye movements were actually prevented, by asking to the subjects to fixate a central target during the search time period. This might be due, at least in part, to the assumption that serial scanning in visual search mainly results from high-speed, covert attentional shifts, basically unrelated to eye movements (the 'mental spotlight' hypothesis: Liversedge & Findlay, 2000).

The results of our study are in good agreement with previous reports on human beings (Zelinsky & Sheinberg, 1997) and monkeys (Motter & Belky, 1998a), which also described a good correlation between the number of saccadic eye movements and search time.

Contrary to our data, Motter & Belky (1998a) found a dependency of the first saccade latency upon the number of stimulus items and the type of visual search (simple feature vs. conjunction search); the duration of subsequent fixations was, however, not dependent on array size and search condition. This discrepancy can possibly be explained (besides the differences in species and search array stimuli) by the dissimilarity in the experimental task. In fact, in the primate study, monkeys were urged to gaze as quickly as possible at the target stimulus. By contrast, our subjects had to perform a simple detection task by pressing a response button, without any mention or requirement regarding the use of eye movements during the visual search.

A more complex pattern of results regarding the first saccadic latency has been reported by Zelinsky & Sheinberg, 1997). A dependency upon the number of stimulus items was found only in the asymmetry tasks whilst, in the simple-vs-conjunction tasks, first saccade latency slightly increased with the number of distractors only in the target-absent trials. Similarly to our data, however, mean noninitial fixation durations did not differ according to search task, number of distractors and presence or absence of the target in the array. This discrepancy for the initial saccade latency in the asymmetry task cannot be readily explained. It should be mentioned, however, that Zelinsky & Sheinberg reported unusually long first saccade latencies (> 300 ms with 5-item stimuli and 500–600 ms with 17-item stimuli). On the contrary, our latencies are much more consistent with the usual reaction times of visually driven saccades (\approx 200 ms). Therefore, motivation or level of arousal might partially explain the difference.

Our results indicate that the difference between the mechanisms involved in different kinds of visual search tasks is quantitative rather than qualitative, and are thus in contrast with the dichotomy between 'attentive' and 'preattentive' type of visual search. The hypothesis of the existence of two distinct visual search strategies, sharply differentiable as far as the allocation of attentive resources and the consequent involvement of distinct brain circuits, has received neurophysiological support from several lines of investigation. In particular, PET (Corbetta *et al.*, 1995) and transcranial magnetic

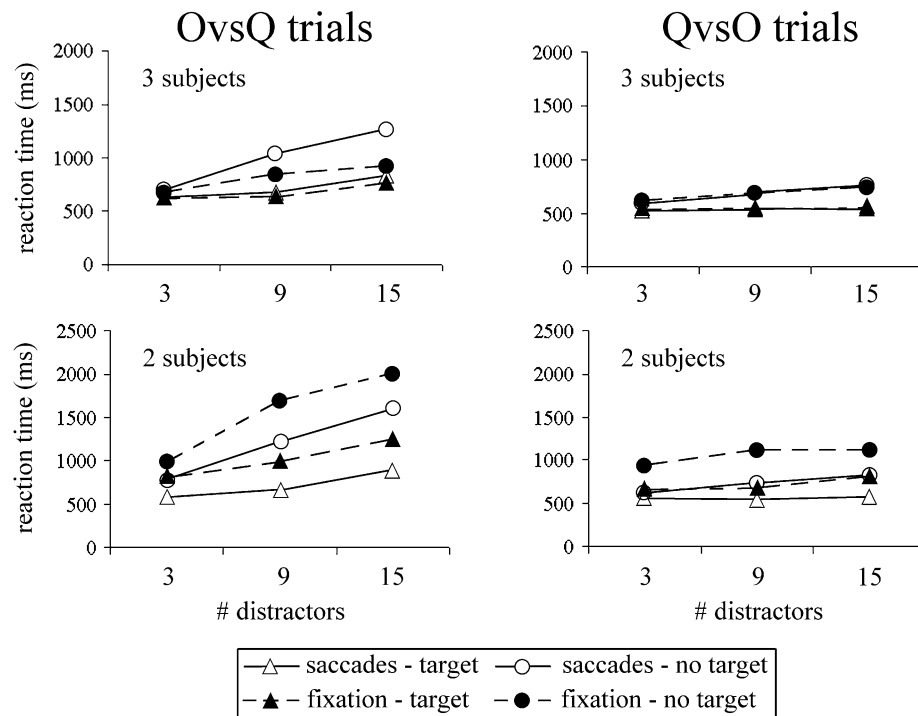


FIG. 7. Mean response times measured in trials in which eye movements were permitted (continuous lines, saccades) or forbidden (dashed lines, fixation), as a function of the number of items in the search array. Triangles and circles represent target-present and target-absent trials, respectively. Subjects could be neatly divided in two groups, extremely homogenous as far as the effects of fixation on reaction times. Upper panels show data from three subjects in which fixation did not affect (or improved) response times with respect to active visual search. Lower panels show data from the two other subjects, in which fixation induced some increase of response times for all stimulus conditions.

stimulation studies (Ashbridge *et al.*, 1997) suggested that posterior parietal cortical areas (PPC), which are considered to be responsible for directing attention in space (Corbetta *et al.*, 1993; Nobre *et al.*, 1997), get selectively engaged during conjunction visual search tasks. Other neurophysiological evidence is, however, compatible with a unitary mechanism. The results of single-cell recordings in the primate inferotemporal (IT) cortex are compatible with a competitive model of visual search (Chelazzi *et al.*, 1993, 1998), whereby even targets defined by complex feature combinations are detected through a parallel processing across the visual field. These IT neurons show very large receptive fields, and are selectively responsive to visual objects like body parts, fruits or plants. When the monkey searches for the presence of a relevant target, IT neurons are initially activated by whichever stimulus they prefer in the choice array. Within ≈ 200 ms from search onset, only cells tuned to the target stimulus remain active, whereas cells tuned to distractors are suppressed.

On the basis of our findings about the timing and scanning paths of eye movements during visual search, we propose a unified conceptual framework, in which both a serial attentive processing of the visual objects and a parallel competitive mechanism for target selection are involved.

A time-limited competitive model for attentive target identification

The observation that the time interval between overt shifts of focal attention, corresponding to single saccadic eye movements (Deubel & Schneider, 1996; Shepherd *et al.*, 1986; Henderson, 1992; Kowler *et al.*, 1995), is independent of the number of stimulus items strongly supports the notion that target selection for the subsequent shift of attention is achieved through a parallel feature analysis, by which several items are simultaneously compared with a target template held in the working memory. This interpretation is in agreement with previous reports, who also investigated the timing of the initial eye movement in human visual search (Findlay, 1997) and of the search saccadic sequence in monkey experiments (Motter & Belky, 1998a).

In this respect, we can safely exclude that, in our experimental conditions, saccades were necessitated by the rapid decline in resolution away from the fovea. In fact, results have clearly shown that our search paradigm could also be successfully completed in the absence of saccadic eye movements, demonstrating that size and details of stimulus items were well within the discrimination capabilities of the visual area covered by the search array.

On the basis of the evidence provided so far, we conclude that, in our experimental paradigm, there is no reason to postulate the occurrence of shifts of visuospatial attention, other than those associated with the executions of saccadic eye movements. Our viewpoint is strongly supported also by the work of Duncan & collaborators (1994), who provided compelling evidence that visual attention is not a high-speed switching mechanism but a sustained state which can last for a few hundred milliseconds. Furthermore, this conceptual frame falls also into line with the 'premotor theory' which proposes the existence of a tight coupling between saccadic motor programming and the allocation of spatial attention (Rizzolatti *et al.*, 1987). In this context, it is interesting to notice that the occurrence of very similar RTs between trials with or without eye movements, observed in the majority of subjects, is highly suggestive that fixation just suppresses overt shifts of attention, without changing the basic search strategy. Accordingly, recent imaging evidence (Corbetta *et al.*, 1998) indicates that the frontal and parietal areas, responsible for attentional shifts, coincide with the areas involved in the execution of saccadic eye movements.

The crucial point that emerges from our results, however, is that the competitive interaction between visual object representations appears to be time-limited. According to this view, a forced election of a candidate target occurs within a temporal gap stochastically distributed around a mean value of ≈ 200 ms. Interestingly, this time interval closely matches the minimum intersaccadic interval build-in in the saccadic control system (cf. Baker, 1989). Furthermore, we have shown that $\approx 30\%$ of all eye movements are not foveation saccades of a single array element, but land in between a group of

items or on an empty space of the visual field. The latencies of foveation and nonfoveation saccades are virtually identical. This observation also suggests that attentional shifts occur at regular time intervals, whether or not the parallel competitive process has been able to provide a candidate target to the computational unit (most likely PPC) responsible for directing attention in space. Single cell recordings in the primate IT cortex (Chelazzi *et al.*, 1993) provide a suitable neurophysiological substrate for how (and where) such a competitive neuronal process would take place. Furthermore, this model predicts that RTs can be accurately predicted by the number of saccades performed during the search task. This prediction is fully supported by our results and is in good agreement with previous reports on human beings (Zelinsky & Sheinberg, 1997) and monkeys (Motter & Belky, 1998a).

Once a candidate target is competitively elected, an overt shift of visuospatial attention is performed. As pointed out in the Results section, it is very unlikely that covert shifts of attention are taking place within the fixation time intervals. If the foveated item is not the target, another parallel processing of the whole stimulus array is performed from a novel point of view, followed by a new shift of focal attention. Thus, search goes on in a loop up to target detection, or up to a decision is made that the target is not present in the array (accounting for the longer search times observed in target-absent trials). If so, the reason why target detection time increases more or less steeply with the number of distractors, depending upon stimulus array properties (Cheal & Lyon, 1992), could conceivably be found in the different levels of signal-to-noise ratio between the target and its environment. Probably, neurons in the IT cortex have 'built-in' the capacity of recognizing more easily certain feature combinations than others. When a difficult feature combination has to be worked out, the search loop for target detection must continue, on the average, for a higher number of cycles.

From an 'ecological' viewpoint, it is conceivable that this mechanism has evolved as the default search strategy in everyday life, where a relevant object has usually to be looked for in a very crowded environment. In this case, it might be much more advantageous to start frequent partial parallel analyses of the visual scene from different points of view, rather than waiting every time for the end of a biased competition process, that slowly converges to a solution because of a unfavourably low signal-to-noise ratio. In fact, neuronal competition must resolve within a sufficiently short time, if a high degree of similarity exists between some element within the currently processed visual area and the target template stored in the working memory. Otherwise, it may be more convenient to explore a different part of the visual field, until the searched target will fall close enough to the line of sight, in the area over which the next parallel competitive process will be operating (Motter & Belky, 1998a).

Our results also provide good evidence that a focal attentive scrutiny of stimulus items is normally required for their full perceptual analysis and, consequently, for achieving a final decision about the presence or absence of the target. This view is supported by the finding that, in those trials ending with a foveation saccade onto the target, a mean delay of ≈ 300 ms occurs between the saccadic eye movement and the time at which the response button is pressed. In this respect, no differences were observed between tasks with flat (QvsO) and nonflat (OvsQ) search functions. It should be noticed that this delay is considerably longer than the mean intersaccadic interval (< 200 ms), indicating that this time gap is certainly long enough for the occurrence of both perceptual processing and motor response preparation. It is interesting to mention that the analysis of lateralized readiness potentials, in externally cued tasks, has demonstrated that move-

ment-related activity over the motor cortex begins not earlier than 120–130 ms before finger movement (Gratton *et al.*, 1988; Praamstra *et al.*, 1999). Thus, the longer latencies we found between eye and finger movements imply that they cannot be regarded as two responses to a common perceptual decision. Rather, the finger motor command is issued after the candidate target, brought into the line of sight by a foveation saccade, has undergone a further perceptual assessment. However, it should also be noticed that a shift of focal attention does not seem to be absolutely required for target detection. In fact, $\approx 25\%$ of search trials are correctly accomplished without making a final foveation saccade onto the target, in both QvsO and OvsQ conditions.

In conclusion, the present findings appear to support a time-limited competitive model for attentive target identification, in which both parallel (competitive) and serial (attentive) processing mechanisms are integrated, as a unified conceptual framework for all kinds of visual search.

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Abbreviations

EOG, electrooculogram; IT, inferotemporal; OvsQ, O target embedded in a field of Q-like distractors; PPC, posterior parietal cortex; QvsO, Q-like target embedded in a field of O distractors; RT, response times.

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