

# Microsaccades distinguish between global and local visual processing

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Much is known about the functional mechanisms involved in visual search. Yet, the fundamental question of whether the visual system can perform different types of visual analysis at different spatial resolutions still remains unsettled. In the visual-attention literature, the distinction between different spatial scales of visual processing corresponds to the distinction between distributed and focused attention. Some authors have argued that singleton detection can be

performed in distributed attention, whereas others suggest that even such a simple visual operation involves focused attention. Here we showed that microsaccades were spatially biased during singleton discrimination but not during singleton detection. The results provide support to the hypothesis that some coarse visual analysis can be performed in a distributed attention mode. *NeuroReport* 18:1015–1018 © 2007 Lippincott Williams & Wilkins.

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## Introduction

When we look for something in a cluttered visual field, the visual system exhibits two distinct patterns of response depending upon whether or not the target of our search is a distinctive element of the scene. A serial, time-consuming, item-by-item, spatially localized scrutiny of the display is necessary to spot the target when it is similar to the other elements [1]. Conversely, when the target has a clear distinctive feature that renders it a singleton, the speed with which the target is found does not slow down as the number of items increases [2]. These different types of visual analyses have their counterparts in the visual-attention literature in the distributed and focused attention modes respectively.

Although it is much easier to search for a singleton compared with a nonsingleton target [3], detecting the singleton presence, localizing it or discriminating its shape are not the same thing, and different attentional mechanisms might underlie these operations of the visual system. Indeed, although a fine-graded singleton shape discrimination requires focused attention, more controversial is whether the simple act of detecting the singleton presence needs focused attention or can be performed in a distributed-attention mode [4,5].

Distinguishing which operations the visual system can perform in a distributed rather than focused attention mode is a central issue for theories of vision. For example, Nakayama's model of vision [6] posits that incoming sensory information from the visual field is represented in the system at different spatial resolutions. At the lowest levels of the system, the information has a fine scale representation; whereas, at the highest levels, the representation is very coarse. According to the type of task, attention

can either operate in a distributed mode at the highest levels or focus on a specific location if it operates at the lowest levels [6]. Results consistent with the focused versus distributed view of attention have been provided [4]. When the color of a singleton target varied unpredictably and a simple detection was required, the response time (RT) × display-size function was basically flat, showing that the target was detected in a distributed attention mode. Instead, when a fine shape discrimination of the singleton was necessary, RTs were overall longer and, crucially, they decreased as the display size increased. This was taken as an index that focused attention was allocated to the target via bottom-up mechanisms whose efficiency increases with greater non-target density [7].

The idea, however, that singleton detection can be performed in distributed attention, is not widely accepted, as it has been challenged by the following studies showing that focused attention would also be involved in such a task [5,8]. Hence, whether the visual system can detect the presence of a singleton in a distributed-attention mode still remains an important unresolved issue.

We recorded, in this study, microsaccades to map the distribution of attention during visual search. Microsaccades are fast tiny eye movements, having a maximum amplitude of 1–2° of visual angle and occurring at about 1–4 Hz during sustained fixation [9–11]. Recently microsaccades have been shown to be modulated by motor [12] and cognitive factors [13], and by visual attention shifts ([9,14]; but see [15]). In particular, the spatial distribution of microsaccades is biased opposite to the location of a peripheral salient event like an abrupt onset [16]. As onsets capture attention and the eyes [17], and as covert attention shifts are accompanied by saccade programming [18], the

bias might be the consequence of an inhibition of the oculomotor activity that would tend to initiate a saccade towards the onset [19].

Here, we took advantage of the close relation between oculomotor activity and attention to investigate whether a different microsaccadic response is observed when a peripheral color singleton, as compared with a fine discrimination of its shape, needs to be simply detected. In terms of the distributed versus focused attentional processing view, the prediction is clear: if singleton detection requires a shift of focused attention, then a spatial bias of microsaccades should emerge both in the discrimination and in the detection task. By contrast, if singleton detection can be performed in distributed attention, microsaccades should be biased only in the discrimination task.

### Experiment

To engage the visual system in either a focused or a distributed attention mode, we used the paradigm introduced by [4]. Participants either had to detect the presence vs. absence of a color singleton target diamond (which should be accomplished in distributed attention) or had to discriminate which side (left vs. right) the target diamond was cut (which should be accomplished using focused attention). The target appeared among a variable number of homogeneously colored distractor diamonds. In both tasks, the color of the target and distractors varied unpredictably, as this is the condition that produces two distinct RT  $\times$  display-size functions in the detection and discrimination tasks. Participants performed the tasks maintaining their gaze at fixation, while we recorded microsaccades.

### Method

#### Participants

Twenty-five students of the University of Trento served as paid volunteers; they were naive as to the purpose of the study.

#### Stimuli

Stimuli were displayed on a CRT 19-inch color monitor, at a viewing distance of 72 cm. The stimuli were equiluminant red and green diamonds (covering approximately  $1^\circ$ ) presented on a black background. Each diamond had a side cut off by approximately  $0.25^\circ$ . The stimuli were arranged on an imaginary circle of  $10^\circ$ . In each trial, the target was unpredictably a red singleton among uniformly green distractors or vice-versa. In target-absent trials in the detection task, all stimuli had the same color.

#### Design and procedure

The experiment consisted of a  $2 \times 3$  factorial design, in which one factor was type of task (detection vs. discrimination) and the other was display size (3, 5, and 12 elements). The discrimination task consisted of 180 trials (60 trials per display size) divided into six blocks of 30 trials each. The detection task consisted of 240 trials divided into eight blocks of 30 trials each: 180 target-present trials (60 trials per display size), and 60 target-absent trials in which participants had to refrain from responding. The factor type of task was blocked (with the order of presentation of the two tasks counterbalanced across participants), whereas the display size was randomized within each block.

### Eye-movement recording

Eye position was monitored binocularly using an Eye-Link II system (SR Research, Osgoode, Ontario, Canada) with a sampling rate of 500 Hz and a spatial resolution of less than  $0.01^\circ$ .

### Microsaccade detection

Microsaccades were detected using the algorithm introduced by [9], adapted to the 500-Hz sampling rate. The algorithm was applied to binocular recording epochs ranging from 1000 ms before target onset to 1000 ms after manual response.

## Results

### Manual response

#### Errors

Errors due to blinks were rare (1.3%) and were not further analyzed. Errors due to broken fixation did not vary across conditions, and were, on average, 20.8%. In the remaining trials, participants' performances were error free in the detection task, whereas errors in the discrimination task did not vary as a function of the display size, and were, on average, 4.2%.

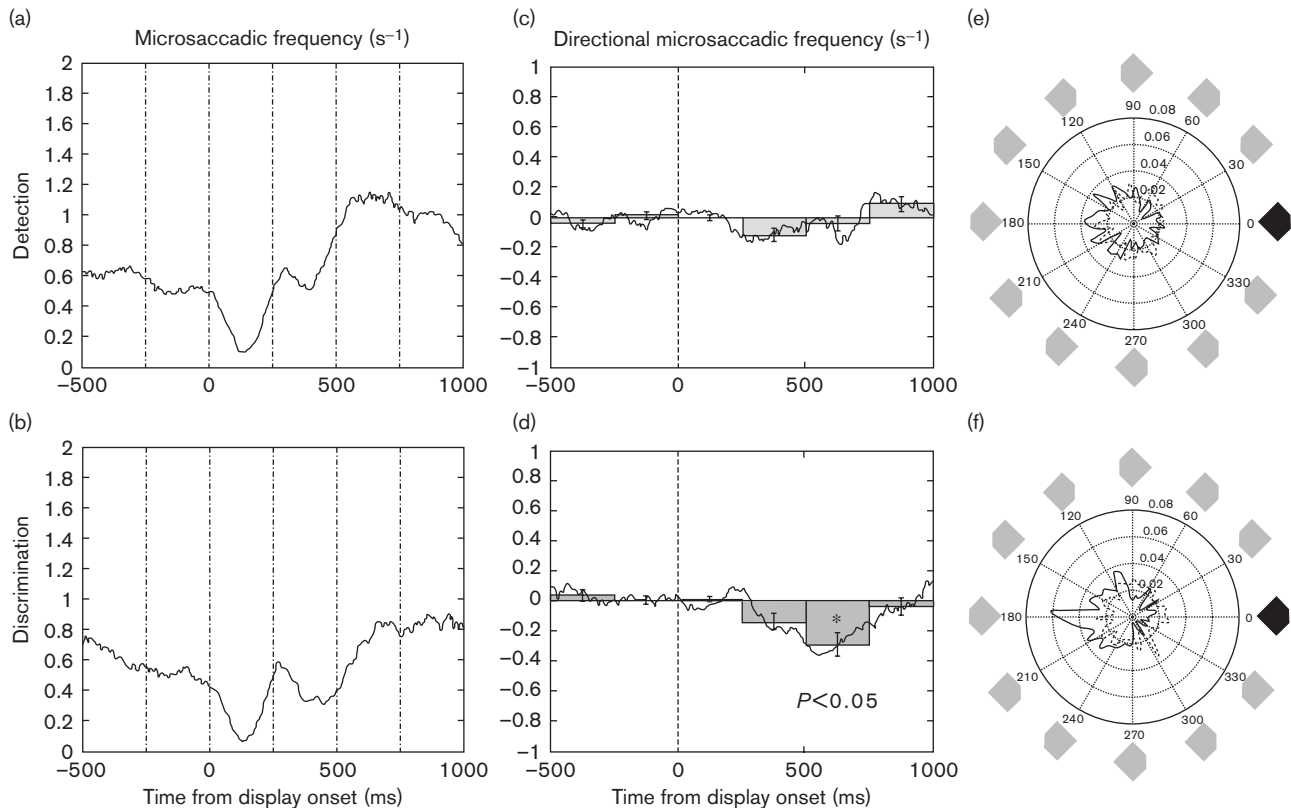
#### Response times

RTs shorter than 150 ms or longer than 2 SD above the mean were trimmed (less than 1.8% of the data). As reported below, six participants were excluded from data analysis because they did not have a sufficient number of microsaccades in each cell of the design. Correct RTs were entered into a repeated-measure analysis of variance, in which the factors were type of task and display size. The main effects of type of task [ $F(1,18) = 234.025, P < 0.0001$ ], display size [ $F(2,36) = 21.189, P < 0.0001$ ], and their interaction [ $F(2,36) = 15.982, P < 0.001$ ] were significant. We replicated the results of Bravo and Nakayama [4], by showing that, when the color of the target varied unpredictably, singleton detection produced a flat RT  $\times$  display-size function (slope  $0.7 \text{ ms/item}, P = 0.41$ ), whereas singleton shape discrimination was accompanied by a negative function in which RTs decreased as the number of distractors increased (slope  $-6.7 \text{ ms/item}, P < 0.0001$ ).

### Microsaccades

Figure 1a and b depicts the evolution of microsaccade frequency in the time window ranging from 500 ms before target onset to 1000 ms after target onset, for both task conditions and collapsed across display size. The frequency of microsaccades was computed over a 100-ms time window moving in 2 ms steps, for each participant and task, and then averaged across participants. As in earlier studies [9], the occurrence of visual onsets in the display (presentation of the search array) produced a clear temporary inhibition of microsaccades, which is evident in both plots in the 0–250-ms time window. The whole recording window was divided into six 250-ms bins, and paired *t*-tests were performed in each bin comparing the frequency of microsaccades in the two task conditions. No significant difference in microsaccade frequency was observed (all *P*'s  $> 0.05$ ; Bonferroni corrected).

The directional frequency of microsaccades (Fig. 1c and d) was defined as the difference between the frequencies of



**Fig. 1** Panels (a) and (b): evolution of absolute microsaccade frequency in the detection and discrimination task. The frequency of microsaccades was calculated over a 100-ms time window moving in 2-ms steps. Dashed vertical lines delimit the time bins used to test for differences in microsaccadic frequency between the task conditions (see Results). Panels (c) and (d): evolution of directional microsaccade frequency in the detection and discrimination task. The frequency was calculated over a 100-ms time window moving in 2-ms steps. Bar plots represent the mean directional frequency in the time bins where *t*-tests have been performed to individuate significant directional biases. Microsaccades present a significant (\*) spatial bias opposite to target location only in the 500–750-ms time window. Error bars represent the between-participants standard error of the mean directional microsaccadic frequency. Panels (e) and (f): polar plots of microsaccade direction relative to the target location in the detection and discrimination task. Microsaccade directions in the –500–0-ms (baseline), and in the 250–500-ms (detection) and 500–750-ms (discrimination) time windows from display onset are represented by dashed and solid lines, respectively. The orientation of microsaccades was realigned such that the target was always at the 0° position. The radii of the plots represent the proportions of microsaccades, the directions of which are contained in 8° angular bins.

microsaccades directed towards the target and of those in the opposite direction. Microsaccades were considered to be directed towards the target if the horizontal component of the movement was positive after that data were normalized by a simple rotation, such that the target was always at the 3-o'clock position. One-sample *t*-tests (two-tailed, Bonferroni corrected) were performed in each temporal bin to establish whether the directional frequency of microsaccades was significantly different from zero. None of the tests was significant in the detection task (all  $P$ 's > 0.05). In the discrimination task, the directional frequency of microsaccades was significantly smaller than zero (thus indicating a bias opposite to the target) in the 500–750-ms time window ( $P < 0.05$ ); whereas, in the remaining five bins, no bias emerged (all  $P$ 's > 0.05). Figures 1e and f show the direction of microsaccades relative to the target locations in the –500–0-ms bin (baseline), and in the 250–500-ms bin for the detection task, and the 500–750-ms bin for the discrimination task. The 250–500-ms bin in the detection task was chosen because the mean RT was 436 ms. Therefore, it would have been uninformative to plot microsaccades in the 500–750-ms bin when the detection task was, for the majority of trials, already completed. In the discrimination task, microsaccades were mainly directed away from the

target after stimulus onset, whereas no significant directional bias was observed in the detection task.

## Discussion

In this study, we used the distribution of microsaccades in a feature-search task to address whether singleton detection can take place in a focused versus distributed attention mode. The logic of using microsaccades to map the attention mode rests on the widely established anatomical [20] and functional [21–22] links between eye movements and attention. Indeed, we all have experienced that it takes some effort to avoid making an eye movement in the direction we are attending to. As microsaccades are kinematically similar to normal saccades (they lie on the main sequence) [23], and as it has been shown that microsaccades can be spatially biased by visual attention [9], one can predict that focused attention shifts would alter the spatial distribution of microsaccades, whereas, obviously, distributed attention would not.

Participants were engaged in a focused versus distributed attention mode by using the paradigm proposed by [4]. When the color of the singleton varied unpredictably, we replicated the findings of Bravo and Nakayama by showing

that singleton detection was accompanied by a flat RT  $\times$  display-size function. By contrast, shape discrimination of the color singleton led to a negative function. As the authors originally proposed, these two qualitatively distinct patterns of RTs suggest that the two tasks might rely on separate attention modes. The microsaccade results are in agreement with this interpretation, as we found a microsaccade bias when the task required fine shape discrimination, namely a shift of focused attention, but no spatial bias, when the task consisted of a simple singleton detection.

The reader may note that the microsaccade bias in the discrimination task was opposite to the location of the singleton, whereas one would have intuitively expected microsaccades to be directed towards the singleton. However, biases opposite to the location of a salient event, like for instance a visual onset, have already been reported in earlier studies [16]. We believe this is due to the fact that the shift of attention necessary to perform the task generates the tendency to initiate a saccade toward the corresponding location [18]. As participants had to maintain fixation, the execution of the programmed saccade required to be counteracted, likely through inhibitory signals descending from the frontal eye fields to the superior colliculus [24]. This, in turn, might have resulted in a general inhibition of all the oculomotor activity (saccadic and microsaccadic) that had a vector congruent with the color singleton position [19]. By contrast, the lack of any microsaccadic bias in the detection task is consistent with the idea that such tasks did not require a shift of attention to the singleton ([4]; but see [5]), eliciting no saccadic activity. As a consequence, microsaccade distribution was spatially unbiased in the detection task. Obviously, one cannot exclude the possibility that, in some trials, the observer might have shifted focal attention to the singleton in the detection task also. This might explain the small, although nonsignificant, microsaccade bias toward the singleton that is observed in the 250–500 ms time window in the detection task. Such shift of attention is, however, not necessary in the detection task [25], whereas it is mandatory in the discrimination task. This view is consistent with the larger microsaccade bias emerged in the latter condition.

### Conclusion

To summarize, our results showed that fixational oculomotor activity (i.e. microsaccades) was spatially biased during a task that required focused attention shifts, whereas no spatial bias emerged during singleton detection, which is in agreement with the idea that such tasks can be performed in a distributed attention mode. Thus, microsaccades can be used as a diagnostic tool to map the current attention mode.

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