# How Longer Saccade Latencies Lead to a Competition for Salience

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## Abstract

It has been suggested that independent bottom-up and top-down processes govern saccadic selection. However, recent findings are hard to explain in such terms. We hypothesized that differences in visual-processing time can explain these findings, and we tested this using search displays containing two deviating elements, one requiring a short processing time and one requiring a long processing time. Following short saccade latencies, the deviation requiring less processing time was selected most frequently. This bias disappeared following long saccade latencies. Our results suggest that an element that attracts eye movements following short saccade latencies does so because it is the only element processed at that time. The temporal constraints of processing visual information therefore seem to be a determining factor in saccadic selection. Thus, relative saliency is a time-dependent phenomenon.

In a scene with many elements, resolution of the visual periphery is often insufficient to resolve the target. For that, eye movements are necessary. Eye movements allow an observer to bring stimulus elements to the central part of the retina, where they can be inspected at a high resolution. Generally, not all elements have to be inspected, as some elements can be excluded on the basis of peripheral information, such as color and shape (Luria & Strauss, 1975). This does not mean that eye movements exclusively land on elements resembling the target. For example, *salient elements* that do not resemble the target can also attract saccades (e.g., Theeuwes, 1991). This finding has resulted in a distinction between *stimulus-driven* and *goal-driven saccades*. Stimulus-driven saccades favor salient elements (those that are in contrast with their surroundings). Goal-driven saccades favor elements that resemble the target.

Recently, the focus of studies on eye movements has shifted from tasks that correlate with either stimulus-driven or goal-driven saccades to tasks that allow researchers to determine when these types of saccades occur (Hunt, von Mühlenen, & Kingstone, 2007; Ludwig & Gilchrist, 2002; van Zoest, Donk, & Theeuwes, 2004). This work has revealed that the proportion of these stimulus-driven and goal-driven saccades varies depending on the duration of the saccade latency. Short-latency saccades are more likely to be stimulus driven, and longer-latency saccades are more likely to be goal driven.

These findings form the basis of the theory that independent bottom-up and top-down processes govern saccadic selection. Bottom-up processes automatically shift attention to the most-salient element in the visual field, and top-down control can disengage bottom-up attention and shift it to elements resembling the target (e.g., Theeuwes, 2010).

Several findings, however, are difficult to explain in terms of independent bottom-up and top-down processes. For instance, if an observer is required to make a speeded eye movement toward the most-salient element in a display that also contains a less-salient element, the latter draws more eye movements as saccade latencies become longer (Donk & van Zoest, 2008). This is not what is expected, as neither bottom-up nor top-down processes should favor the less-salient element. Yet, with longer-latency saccades, less-salient elements become more likely to be targeted. Generally, the proportion of eye movements toward the most-salient element decreases as the length of latencies increases, even when the most-salient element is the target (e.g., Van Zoest & Donk, 2008). Because

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this decrease appears to be a general phenomenon, the question rises whether it is the result of time-related aspects of processing visual information.

During the saccade latency, the decision of where to move next is made. This decision is limited to elements that have been detected at the moment the eye movement is programmed. It is already known that as fixation durations increase, saccades become more selective, and search becomes more efficient (Hooge & Erkelens, 1998, 1999). This indicates that with more time to process stimulus information, the set of potential targets can be reduced. That is, having more information available allows observers to reject some distractors as potential targets. However, before an element can be rejected, it needs to be detected by the visual system. Hence, initially longer processing will lead to the detection of more elements and, thus, an increase of the potential target set. Therefore, the temporal aspects of processing can possibly explain the existence of stimulus-driven and goal-driven saccades. After short time periods, only salient elements have been processed, thus top-down decisions will appear stimulus driven. Longer processing allows for a more informed saccade, which will appear goal driven.

The time it takes to detect an element depends on its visual properties. Physiological research has revealed many visual properties that influence processing speed. In the experiments reported here, we took advantage of these properties to create stimuli through which we could control which element would be detected first. For instance, compared with high-spatial-frequency (HSF) stimuli, low-spatial-frequency (LSF) stimuli evoke responses at shorter latencies (e.g., Mazer, Vinje, McDermott, Schiller, & Gallant, 2002; Parker & Salzen, 1977). Also, higher-contrast stimuli evoke responses at shorter latencies than lower-contrast stimuli do at several stages of processing, for instance, at the retina (Shapley & Victor, 1978) and at the primary visual cortex (Albrecht, 1995; Carandini, Heeger, & Movshon, 1997).

Methods that can be used to influence processing time have been introduced in psychophysical studies. For example, Schyns and Oliva (1994) showed that in a single stimulus, information can be presented in such a way that it is processed at different moments in time. In their experiment, they used hybrid images, which are a superimposition of two scene images, one filtered at an LSF and one at an HSF. Varying presentation durations led observers to have different perceptual experiences. For short presentation durations, a bias toward reporting the scene filtered at the lower spatial frequency was found, but longer presentation durations led to more frequent reports of recognizing the scene filtered at the higher spatial frequency. However, we should note that Schyns and Oliva attributed the perceptual differences across presentation durations to coarse-to-fine scene recognition, rather than processing times. Nevertheless, this study demonstrates an elegant way to present information that will be processed at different speeds in the same location in the visual field.

In the study reported here, we investigated whether the temporal aspects of encoding visual information can explain the time-limited attraction of a salient element. We used hybrid images in a search display; these images had controllable visual characteristics with different processing times. As we wanted to limit the influence of top-down inputs, we asked observers to make an eye movement toward either of two target deviations in the stimulus. This allowed us to evaluate the relation between the processing speed and selection in saccades with different latencies. We expected this procedure to provide similar results as those that form the basis for the theory that bottom-up and top-down processes compete in saccadic target selection.

## Experiment 1

The central question in our first experiment was whether temporal aspects of encoding visual information govern saccadic target selection. To test this, we created a stimulus containing target deviations on two superimposed grids that required different processing times. One grid could be processed faster because it was filtered at a lower spatial frequency, but a second grid required more time to process because it was filtered at a higher spatial frequency (e.g., Mazer et al., 2002; Parker & Salzen, 1977). If saccadic selection is indeed limited by the temporal aspects of processing, a bias toward the deviation in the LSF grid should appear following short saccade latencies. This bias should disappear following longer saccade latencies.

### Method

***Observers.*** Seven observers (age range = 22 to 30 years), including one of the authors (J. P. de Vries), participated in the experiment. All except J. P. de Vries were naive to the goal of the experiment and had normal or corrected-to-normal vision. Observers either worked or studied at Utrecht University and participated on a voluntary basis.

***Stimuli and apparatus.*** The stimulus consisted of two grids containing 144 rectangles each (arranged in a regular 12 × 12 pattern). All rectangles on each grid were oriented vertically (nontargets) except for one (the target), which deviated at an angle of 45°, either clockwise or counterclockwise. The two grids were filtered at different spatial frequencies, one using a bandwidth filter with a primary frequency of 6.5 cycles/° (the HSF grid) and one using a bandwidth filter with a primary frequency of 3 cycles/° (the LSF grid). The root-mean-square contrast of the filtered grids was equalized. The two grids were superimposed, creating a single grid containing 142 nontargets and 2 targets. An example of the stimulus is shown in Figure 1.

A target was placed at one of eight possible locations on the grid, each at equal distance (6.1°) from the central fixation dot. Two additional constraints were applied to the placements of the two targets. First, targets were never placed in the same location as in the previous trial. This was done because latencies of saccades toward targets in the same location as in the previous trial are longer than latencies of saccades toward targets in different locations (Carpenter, 2001). Second, the two targets were never placed in adjacent locations. This was done
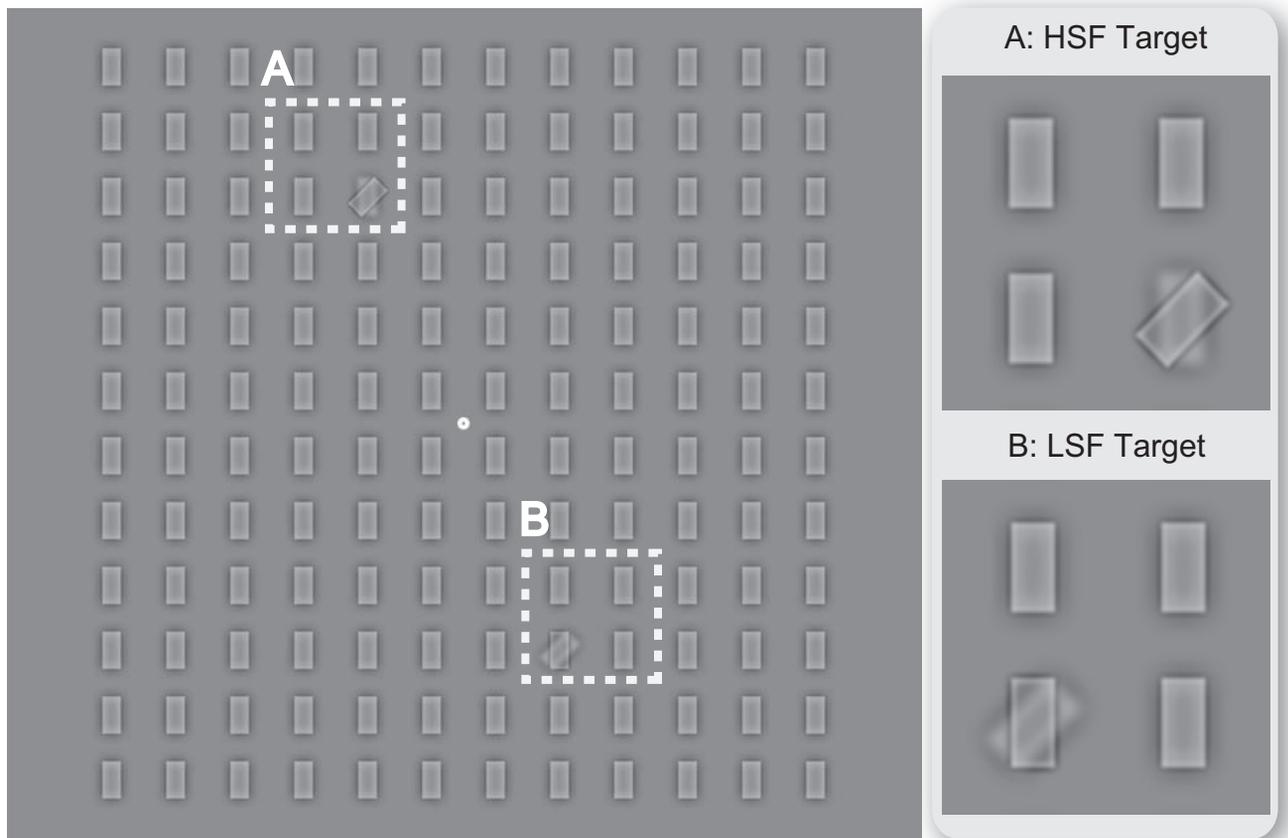
**Fig. 1.** Example stimulus used in Experiment 1. Two grids, one filtered at a high spatial frequency (HSF) and one filtered at a low spatial frequency (LSF), were superimposed, as illustrated at the left. Each grid contained 143 vertical rectangles (nontargets) and 1 rectangle tilted 45° (target), either clockwise or counterclockwise. Targets were located at equal distances (6.1°) from the central fixation dot. The illustrations on the right are enlargements of the areas containing the two targets in this example: one in the HSF grid and one in the LSF grid.

to make sure they were at a sufficient distance from each other to avoid saccades landing between the targets, a phenomenon known as the *global effect* (Findlay, 1982).

The stimuli were programmed in MATLAB (The Math-Works, Natick, MA) and generated on an Apple G4 computer. They were displayed on a LaCie (Harmelen, The Netherlands) 22-in. CRT monitor with a refresh rate of 75 Hz at a resolution of 1,600 by 1,200 pixels. Eye movements were recorded using an Eyelink II system (SensoMotoric Instruments, Montreal, CA) at a frequency of 500 Hz. The observer's head was supported by a chin rest at a distance of 64 cm from the screen.

*Eye movement analysis.* The stimuli were viewed binocularly, but eye movements were recorded from the left eye only. Eye movement data were collected for off-line analysis. Saccades were defined as movements with a minimum velocity of 20°/s; after a saccade was detected, its start point and end point were determined by looking backward and forward in time to determine when its velocity dropped below 2 standard deviations higher than the velocity during fixations (for details, see Van der Steen & Bruno, 1995). Saccades with amplitudes under 1.5° were removed from the analysis. If a small saccade was removed, fixations before and after this saccade were combined

by averaging their locations. Also, fixation durations shorter than 50 ms were discarded from further analysis.

The first saccade of each trial was categorized on the basis of its end point. If the end point was within 2.3° of one of the target deviations (a similar range was used by Donk & van Zoest, 2008), it was considered as targeting that deviation. If it was not within 2.3° of either the LSF or the HSF deviation, it was discarded from analysis.

*Procedure.* After observers were familiarized with the setup, an example of the stimulus was shown. The observers were instructed to make an eye movement as fast as possible toward either of the two deviating targets. The fixation dot then appeared at the center of a gray screen. Trials (400 per observer) were initiated by pressing the space bar on a keyboard, after which the fixation dot became slightly smaller to indicate that the trial had been initiated. After a random interval ranging from 500 ms to 1,000 ms, the stimulus appeared, and observers were allowed to move their eyes. When observers located a target, they responded by pressing the "0" key on the keyboard's numeric keypad. On half of the trials, the fixation dot remained visible during the trial, so we could obtain a larger variation in saccade latencies (McSorley, Haggard, & Walker, 2006).
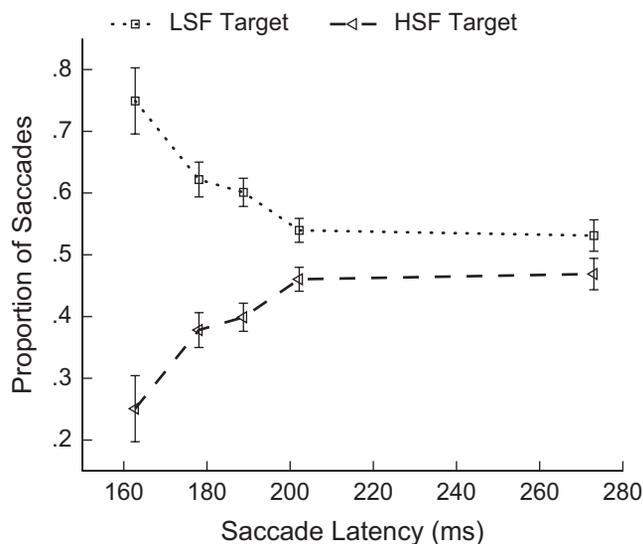
**Fig. 2.** Results from Experiment 1: mean proportion of saccades toward targets with low spatial frequencies (LSFs) and toward targets with high spatial frequencies (HSFs) as a function of saccade latency. Saccades were sorted in ascending order and divided into five bins of equal size, and each point in the graph represents the results of one bin. Error bars denote standard errors of the mean.

## Results

To evaluate saccadic selection over a range of saccade latencies, we sorted the latencies in ascending order and split them into five bins of equal size. The proportions of saccades toward each element are plotted in Figure 2. Following short saccade latencies, there was a clear bias toward the LSF target. However, the proportion of eye movements toward the LSF target declined as the duration of saccade latencies increased, $F(4, 24) = 13.89$, $p < .001$ (repeated measures ANOVA), with follow-up polynomial contrasts indicating a significant linear effect, $F(1, 5) = 23.276$, $p < .01$. For the longer saccade latencies, this bias disappeared, and the HSF target was selected with nearly equal frequency.

## Discussion

The shift from targeting only the LSF deviation to targeting the LSF and HSF deviations with equal frequency demonstrates that prolonged visual processing of the stimulus allows for the detection of more potential targets. In other words, although only the LSF target was detected in the case of short saccade latencies, more processing time allowed for the detection of the second target, which then also competed in the process of saccadic selection. This suggests that the attraction toward the most-salient element was a side effect of this element being processed faster than a less-salient element. At the moment of the saccadic decision, visual processing appears to have not yet been completed. So, rather than a competition between elements for attention, some elements were processed and others had not yet been processed at the time the saccadic decision was made.

To exclude effects of contrast, we equalized the root-mean-square contrast of both the LSF rectangles and the HSF rectangles (the elements that formed the respective grids). The findings suggest that temporal aspects of processing visual information govern saccadic selection. However, in this experiment, only the spatial frequency of each grid was varied to influence processing speed. Many other visual properties also influence processing speed. To verify that the effects we found are generally applicable and not just related to an odd preference for LSFs, we also manipulated the contrast of the two grids in Experiment 2.

## Experiment 2

To verify that the transient bias toward the LSF target was indeed due to the temporal aspects of processing visual information, we conducted Experiment 2, in which we manipulated the speed at which elements are processed by varying the luminance contrast of the grids. High-contrast stimuli are processed faster than low-contrast stimuli (Albrecht, 1995; Carandini, Heeger, & Movshon, 1997), and, as a result, contrast should also influence saccadic selection as a function of latency. Increasing the contrast of a grid allows for faster processing, and therefore the target in this grid should be selected more frequently following short saccade latencies than following long saccade latencies. To test these predictions, we manipulated the contrast of both the LSF and HSF grids independently over two conditions.

## Method

**Observers.** Six observers from the same pool used in the first experiment participated in Experiment 2; 4 of the observers were naive to the goal of the experiment. The two other observers (J. P. de Vries and I. T. C. Hooge) were coauthors of this article.

**Stimuli and apparatus.** The stimulus design was similar to that used in Experiment 1, except that the luminance contrast of each grid was varied independently. In the LSF-contrast condition, the luminance contrast of all LSF rectangles was doubled. In the HSF-contrast condition, the luminance contrast of all HSF rectangles was increased by 50% of the original contrast. Figure 3 shows details of the HSF and LSF target areas for the two contrast conditions.

**Procedure.** The only difference in the procedure from Experiment 1 was that Experiment 2 featured two conditions that were tested in two blocks. The order of the blocks (200 trials) was randomized for each observer.

## Results and discussion

The proportions of saccades toward each target are plotted in Figure 4 for the two conditions and show the effect of the
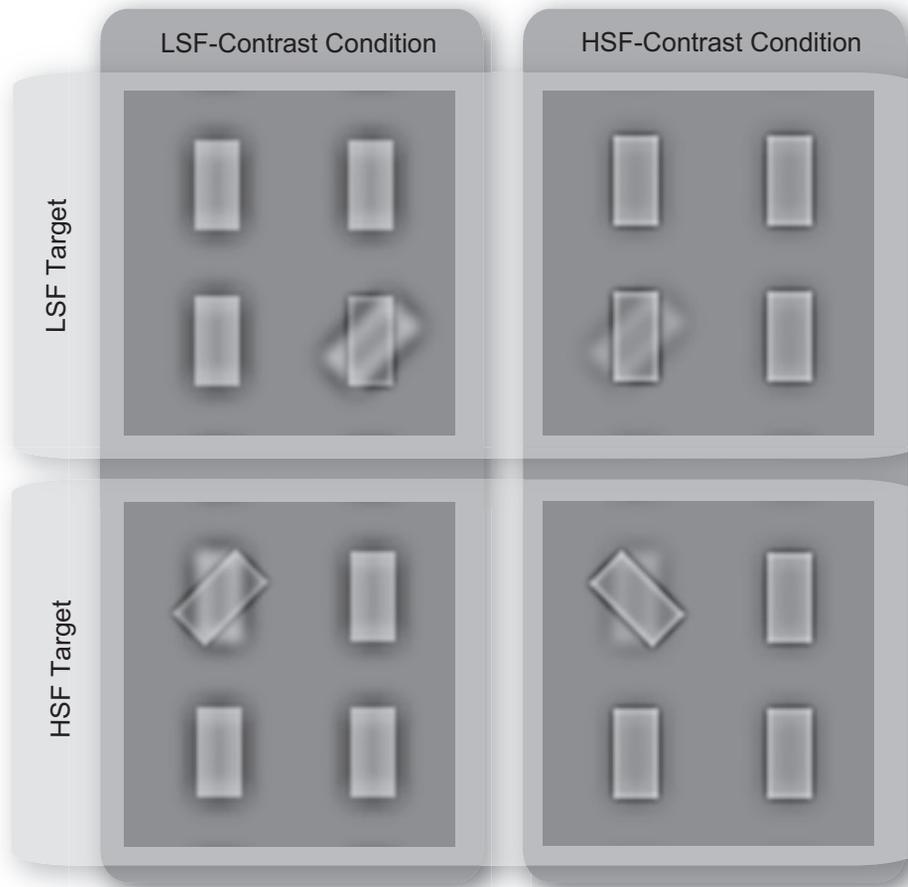
**Fig. 3.** Details of an example stimulus used in Experiment 2. The stimulus was the same as in Experiment 1, except that the luminance contrast of the low-spatial-frequency (LSF) grid and that of the high-spatial-frequency (HSF) grid were varied independently. The illustrations show target areas for targets in the LSF grid and targets in the HSF grid in the LSF-contrast condition and the HSF-contrast condition. In the LSF-contrast condition, the luminance contrast of all LSF rectangles was doubled; in the HSF-contrast condition, the luminance contrast of all HSF rectangles was increased by 50%.
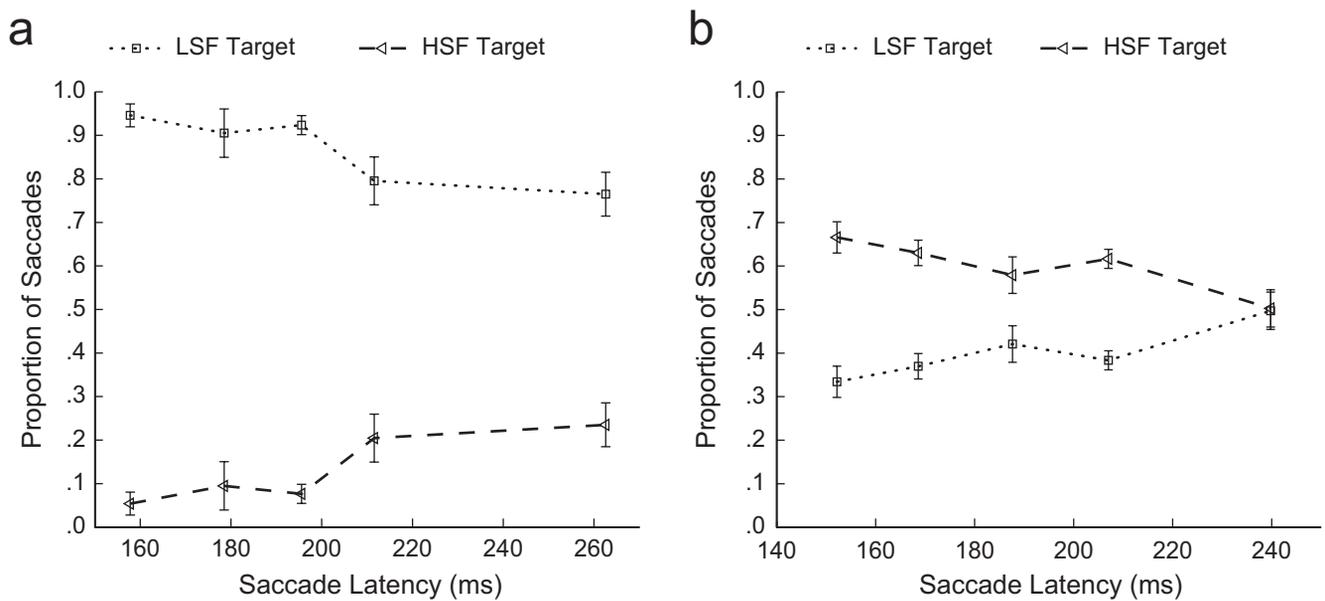


**Fig. 4.** Results from Experiment 2: mean proportion of saccades toward targets with low spatial frequencies (LSFs) and toward targets with high spatial frequencies (HSFs) as a function of saccade latency. Results are shown for (a) the LSF-contrast condition and (b) the HSF-contrast condition. Saccades were divided into five bins of equal size, and each point in the graph represents the results of one bin. Error bars denote standard errors of the mean.

respective contrast manipulations. In the LSF-contrast condition, bias toward the LSF target increased (Fig. 4a). In the HSF-contrast condition, bias shifted toward the HSF target (Fig. 4b).

It seems counterintuitive that in the LSF-contrast condition, the bias toward the LSF target did not disappear completely following long saccade latencies. However, this can be explained by the large difference in processing speed. Although in Experiment 1, the distribution of processing time for the two grids still overlapped—even for the shortest-latency saccades, the HSF target was selected occasionally—in the LSF-contrast condition, the increased contrast of the LSF grid led to very little overlap in processing times for the LSF and HSF grids (in this condition, short-latency saccades almost exclusively targeted the LSF deviation). The latency of the saccade is known to reflect the time needed to decide whether a target is present (Carpenter & Williams, 1995). In Experiment 2, it is most likely that the decision to initiate an eye movement toward the LSF target was made before the presence of the HSF target was detected.

## General Discussion

Visual features in the periphery play an important role in the selection of potential targets (e.g., Luria & Strauss, 1975). The detection threshold of these different features is time dependent (e.g., Geisler & Chou, 1995). That is, some features require more processing time than others. As a consequence, early in the saccade latency, the presence of some features may not be detected yet. But as time progresses, the number of potential targets in a search task will increase, simply because more features are processed and their probability of being detected will rise. In the experiments reported here, we investigated whether the attraction of elements at short saccade latencies (elements that are often referred to as salient,[1] e.g., van Zoest et al., 2004) can be explained by the fact that only these elements have been processed.

In two experiments, we manipulated the spatial frequency and contrast of two superimposed grids. Each grid contained one deviating element that served as a target, which meant that the superimposed grids featured both an LSF target and an HSF target. Because both contrast and spatial-frequency variations influence processing speed, we were able to create stimuli in which one target required a short processing time and one required a long processing time. In both experiments, we found that short-latency saccades were biased toward the target in the grid requiring shorter processing times. The resulting patterns were very similar to those found in previous studies (e.g., van Zoest & Donk, 2006; van Zoest et al., 2004); such results originally led to the theory that competing bottom-up and top-down processes underlie saccadic selection. The experiments reported in this article provide converging evidence that not all targets have been detected at the moment of the saccadic decision. With longer latencies, more visual information is processed and, hence, saccadic selection is based on a larger number of potential targets. The initial attraction of a target is therefore likely the result of the fact that it is the only target that has been processed at the time of the saccade decision. Elements that attract attention are generally considered salient, but the limited lifetime of this attraction suggests that saliency is not an entity as such but a time-dependent phenomenon.

Regarding the nature of potential targets, Hooge and Erkelens (1999) showed that peripheral selection becomes more efficient at longer fixation durations. This suggests that, over time, more elements are identified and rejected as potential targets. Because identification follows detection (Nothdurft, 2002b), elements can be rejected as potential targets only after they are detected. Elements detected first are also the first to be considered potential targets. This suggests that rather than a competition between bottom-up and top-down processing, stimulus-driven and goal-driven saccades are merely a reflection of how much information has been processed and is therefore available at any given time.

The distinction between detecting the presence of an element and identifying the element can also shed new light on oculomotor capture. Bacon and Egeth (1994) suggested that capture by a salient task-irrelevant element may occur because observers have adopted a strategy for searching an odd form, even though the specific target form was known. If processing during short saccade latencies simply has not revealed enough information to identify the target, a saccade toward the most-salient item can be considered a task-relevant decision. In experiments studying saccade latencies, observers are typically asked to make an eye movement as quickly as possible. Creating a sense of urgency can influence the decision criterion (Reddi & Carpenter, 2000). In this case, faster responses are likely to force observers to rely only on the detection of elements, without allowing enough time to reject elements as potential targets on the basis of their identity. Truth be told, the validity of such findings is still the subject of debate (Leber & Egeth, 2006; Theeuwes, 2004).

The decreasing attraction of a salient element over time has previously been attributed to active inhibition of the respective element (Godijn & Theeuwes, 2002; McSorley et al., 2006), as well as passive decay of its strength (Cheal & Lyon, 1991; Nakayama & Mackeben, 1989; Nothdurft, 2002a; Yantis & Jonides, 1990). Active inhibition cannot explain the results of the present experiments, as there was no need to inhibit the salient target, and observers could target either element. However, the decreasing attraction of a salient element over time can be due to more than just passive decay. Rather than an absolute decay of activation, it seems that with longer latencies, more information has been processed. As a result, an element loses its salience in a relative way, as more competing elements are uncovered.

When varying spatial frequencies and contrasts and considering timing issues, it is tempting to look at differences between magnocellular and parvocellular pathways. However, it is hard to stimulate a single pathway exclusively (Merigan & Maunsell, 1993), and our stimuli surely did not. Nevertheless, our results seem to be compatible with the spatial frequency

and timing characteristics attributed to these parallel pathways. It is, however, still a matter of debate on how these pathways relate to attentional guidance, and more research is necessary to see whether our findings are in conflict with such work. Clearly, attention has different effects on the different pathways, but the results so far are not clear (e.g., Nieuwenhuis, Jepma, La Fors, & Olivers, 2008; Snowden, 2002). Furthermore, the results of studies focusing on processes further along the visual pathway are less ambiguous. Looking beyond these pathways, in areas involved in saccadic selection, previous studies have documented that neural responses are consistent with the findings of our experiments. For example, in a recent study in which monkeys had to perform a feature-search task, models were evaluated on their ability to predict both response times and activation in movement neurons in the frontal eye fields. This demonstrated that gated models, in which neurons in the frontal eye fields accumulate evidence over time, correspond well with behavioral data (Purcell et al., 2010). The question of where this information originates is an issue for future research.

The results of several physiological studies dealing with the creation of a saliency map are in line with our findings. Studies that show that relative salience is a temporal phenomenon—a side effect of the moment at which they have been processed—are one such example (Thorpe, 1990; VanRullen, Guyonneau, & Thorpe, 2005). Also, on the basis of responses from primate striate complex cells, Gawne, Kjaer, and Richmond (1996) reported that a cell's response latency is related to the contrast in the stimulus. This was not reflected in the cells' response rate. It appears that the difference in the neural substrates is encoded in latency rather than in amplitude. Hence, a saliency map will initially include only the first-detected element, but over time it becomes more complex as more elements are detected and represented in the map. The content of the saliency map is therefore time dependent, and its complexity grows over time.

In conclusion, recent studies have shown that even when the most-salient element is the target, the number of eye movements toward the target decreases as saccade latencies lengthen. This finding is difficult to reconcile with a shift from bottom-up processes to top-down control of eye movements. Our findings show that the temporal aspects of visual processing can explain this decrease in performance. These results suggest that, at the time the saccade is initiated, visual processing is not complete, and the set of potential targets is therefore limited to those that have been processed enough to be detected. Relative saliency is therefore a time-dependent phenomenon.

This theory does not rule out bottom-up and top-down influences, but rather than presenting them as competing, it posits an additive approach. A top-down decision is always made, but it depends on the state of bottom-up processing; ongoing bottom-up processes continually reveal more information, and this allows for a more-informed saccadic decision.

## Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

## Note

1. Saliency is a term that is used in many different ways. Although some researchers consider saliency to be a physical stimulus property, we define saliency as a subjective entity.

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