

The Role of Stimulus-Driven and Goal-Driven Control in Saccadic Visual Selection

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Four experiments were conducted to investigate the role of stimulus-driven and goal-driven control in saccadic eye movements. Participants were required to make a speeded saccade toward a predefined target presented concurrently with multiple nontargets and possibly 1 distractor. Target and distractor were either equally salient (Experiments 1 and 2) or not (Experiments 3 and 4). The results uniformly demonstrated that fast eye movements were completely stimulus driven, whereas slower eye movements were goal driven. These results are in line with neither a bottom-up account nor a top-down notion of visual selection. Instead, they indicate that visual selection is the outcome of 2 independent processes, one stimulus driven and the other goal driven, operating in different time windows.

Theories of visual search generally differentiate between stimulus-driven and goal-driven selection. Stimulus-driven selection occurs when visual selection is determined by the stimulus properties in the visual field (see, e.g., Theeuwes, 1991; Yantis & Jonides, 1990). Goal-driven selection takes place when observers are able to select those stimuli that are in line with a set of goals allowing them to perform a certain task (see, e.g., Bacon & Egeth, 1994; Folk, Remington, & Johnston, 1992). In most studies, these two modes of visual selection have been contrasted, with evidence obtained for either stimulus-driven or goal-driven control.

However, rather than focusing on whether stimulus-driven or goal-driven selection dominates behavior, it may be more appropriate to ask when these forms of selection dominate behavior (see also Ludwig & Gilchrist, 2002). Over the next few paragraphs, the evidence in support of stimulus-driven and goal-directed control of attention is reviewed. Evidence indicates that both forms of selection occur but operate in different time windows: Stimulus-driven control dominates selection early on, whereas goal-driven control dominates selection later. After showing that previous studies may be reinterpreted in this fashion, we present evidence from four experiments directly in support of our contention.

Several authors have argued that visual selection is predominantly stimulus driven (Itti & Koch, 2000; Nothdurft, 2002; Theeuwes, 1991, 1992, 1994). According to this bottom-up view, salient properties are assumed to attract attention (and possibly the eyes) irrespective of the goals and intentions of the observer.

Goal-driven control does play a role but only after attention has been captured by a salient element (Nothdurft, 2002; Theeuwes, 1992; Theeuwes, Atchley, & Kramer, 2000). That is, the goals and intentions of an observer determine whether a selected object remains to be selected or is discarded. Thus, goal-driven control is assumed to be conditioned on stimulus-driven control: Goal-driven control is able to affect performance only after an object has been selected in a stimulus-driven fashion. Evidence for this view typically stems from the irrelevant singleton paradigm (Theeuwes, 1991, 1992, 1994; Yantis & Jonides, 1990). In the irrelevant singleton paradigm, participants search for a singleton target among a number of nontargets. On some trials, an irrelevant (salient) singleton distractor is presented concurrently with the presentation of the search display. Search performance in the no-distractor condition is compared with that in the distractor condition. For example, in the no-distractor condition, Theeuwes (1992) presented displays consisting of one singleton target (a green circle) and multiple nontargets (green diamond shapes). In the distractor condition, an irrelevant singleton distractor (a red diamond shape) was also present in the display. The task of participants was to indicate the orientation of a line segment appearing in the singleton target. The results showed that the presence of an irrelevant singleton distractor disrupted search. Participants were slower to indicate the line orientation of the target singleton when an additional distractor was present. Furthermore, it was shown that selectivity depended on the relative salience of the singleton target and distractor. When the singleton distractor was made less salient than the target, it no longer interfered with search for the singleton target. These results are in line with the bottom-up view arguing that visual selection is initially determined by the salience of stimuli in the visual field. Accordingly, the location containing the most salient stimulus is granted attention before all other locations. Following inhibition of the most salient location, the location containing the next salient element receives spatial attention and so forth until the target is found (Wolfe, 1994).

The idea that visual selection is primarily determined by the stimulus properties in the visual field has recently been extended to the oculomotor domain (Godijn & Theeuwes, 2002; Irwin, Col-

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This work was supported by the Netherlands Organization for Scientific Research.

We thank Jillian Fecteau and Diego Fernandez-Duque for their helpful comments on earlier versions of this article. We also thank Stephan Dekker for technical assistance.

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combe, Kramer, & Hahn, 2000; Kramer, Irwin, Theeuwes, & Hahn, 1999; Theeuwes, Kramer, Hahn, & Irwin, 1998; Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999). For example, Theeuwes et al. (1998, 1999) asked participants to make a voluntary, goal-directed saccade to a color singleton target. In half of the trials, simultaneous with the presentation of the color singleton target, a new element was presented with an abrupt onset somewhere in the display. The results showed that the planning and execution of the goal-directed saccade toward the singleton target were disrupted by the appearance of the new element. On a substantial portion of the trials, the eyes first moved to the distractor (i.e., the onset) before moving to the target (i.e., the color singleton). These results again suggest that visual selection is initially stimulus driven. Irrelevant salient singleton distractors may capture not only attention but also the eyes.¹

Contrary to the view that visual selection is stimulus driven at first, other authors have argued that visual selection is initially goal driven (Bacon & Egeth, 1994; Folk & Remington, 1998; Folk et al., 1992; Folk, Remington, & Wright, 1994). According to this top-down view (e.g., Folk et al., 1992), visual selection is contingent on attentional control settings induced by the task demands. This implies that only stimuli that match the goal-driven control settings will be selected, whereas stimuli that do not match these settings will not be selected. Accordingly, stimulus-driven control is assumed to be contingent on goal-driven control. Evidence for this view typically stems from studies using a cuing paradigm. For instance, in Folk et al. (1992), participants were asked to indicate the identity of a target (X or $=$) presented as a single onset for one group of participants or as a color singleton for another group of participants. Prior to the presentation of the search display (150 ms), a peripheral location precue was presented at one of four potential target locations. The relation between cue property and target property was systematically manipulated, that is, both a red target and an onset target could be preceded by a red singleton cue or an onset cue. The results showed that an invalid location cue disrupted search performance only if the cue possessed a stimulus property related to that of the target. If observers were set to search for color, a color cue disrupted performance, whereas an onset cue did not. If observers were set to search for an onset, an onset cue disrupted search, but a color cue did not. The authors concluded that the visual selection of a stimulus event is "contingent on whether that event shares a feature property that is critical to the performance of the target task" (Folk et al., 1992, p. 1041).

Even though multiple studies have been concerned with the control of attention and eye movements, the question of whether visual selection is ultimately dominated by stimulus-driven or goal-driven control is still unresolved (see, e.g., Wu & Remington, 2003). However, it need not necessarily be the case that visual selection is dominated either by stimulus-driven processes or by goal-driven processes. Instead, it is possible that both stimulus-driven and goal-driven control independently contribute to visual selection by being operational in different time windows. In other words, whether visual selection is stimulus driven or goal driven may be determined by the point in time at which the response is triggered after the presentation of the stimuli (Ludwig & Gilchrist, 2002). It is feasible that the interference found in the irrelevant singleton paradigm is purely stimulus driven in the sense that goal-driven control is not yet possible when target and distractor are simultaneously presented. If, however, the presentation of the

distractor precedes that of the target, as in the cuing paradigm of Folk et al. (1992), observers might have ample opportunity to override stimulus-driven interference and perform in accordance with the task demands (Ludwig & Gilchrist, 2002). There are various studies suggesting that stimulus-driven and goal-driven selection indeed operate in different time windows (see, e.g., Cheal & Lyon, 1991; Godijn & Theeuwes, 2002; Ludwig & Gilchrist, 2002; Nakayama & Mackeben, 1989). For instance, Godijn and Theeuwes (2002), using the same paradigm as Theeuwes et al. (1998, 1999), demonstrated that if observers had to make a speeded saccade toward a color singleton target, the presentation of an irrelevant onset singleton distractor significantly disrupted search performance. More important in the present context, however, is the finding that the fastest saccades were typically directed to the onset singleton distractor, whereas the slowest saccades were mostly directed toward the color singleton target. These results suggest that early in time, eye movements are completely stimulus driven, whereas later in time, top-down knowledge is available, enabling the eyes to go directly to the target.

Similar findings were reported by Ludwig and Gilchrist (2002). Observers searched for a color singleton target among three non-targets. Observers were required to indicate the target location manually or by making a saccadic eye movement. An additional distractor appeared with or without luminance onset. The results showed that the relative contribution of stimulus-driven and goal-driven control in visual selection depended, among other things, on the latency of the evoked response. More specifically, relatively slow manual responses were much less affected by distractor onset than were relatively fast eye movements. Moreover, Ludwig and Gilchrist performed several post hoc analyses to compare the effect of onset for fast and slow manual responses separately. The analyses showed that fast manual responses were, like saccadic responses, significantly affected by distractor onset. Together, the above results strongly suggest that timing is a critical issue in determining whether visual selection is stimulus driven or goal driven: Early in time, visual selection appears to be predominantly stimulus driven, whereas later on, selectivity appears to be goal driven.

The aim of the present study was to distinguish between a bottom-up, a top-down, and a timing view of visual selection. Whereas the first two theoretical notions assume an explicit contingency between stimulus-driven and goal-driven control, the last account assumes both processes to independently contribute to visual selection. That is, early in time, visual selection is assumed to be purely stimulus driven, whereas later on, visual selection presumably is goal driven. It is important to note that a timing account does not assume any contingency between stimulus-driven and goal-driven control. Instead, both types of control are assumed to independently contribute to visual selection. Furthermore, both are assumed to be operational in different time windows. In other words, at the moment in time that goals and intentions of an observer affect visual perception, stimulus-driven activation is

¹ This latter finding is in line with the idea that there exists a close coupling between the attentional and oculomotor system movements (see, e.g., Deubel & Schneider, 1996; Godijn & Pratt, 2002; Hoffman & Subramaniam, 1995; Kowler, Anderson, Doshier, & Blaser, 1995; McPeck, Maljkovic, & Nakayama, 1999; Moore & Armstrong, 2003).

assumed to have decreased to a minimum: In this sense, stimulus-driven factors do not contribute to the ability to intentionally select a location in space.

To distinguish between bottom-up, top-down, and timing accounts of visual selection, in the present study, we investigated the relative contribution of stimulus-driven and goal-driven control to saccadic visual selection as a function of time. Saccadic eye movements are well suited to gaining insight into the manner in which stimulus-driven and goal-driven control contribute to visual selection in time. Eye movements can be more rapidly evoked than manual responses and therefore allow a greater insight into the early processes of visual selection (see, e.g., Ludwig & Gilchrist, 2002). Moreover, saccadic eye movements provide accurate information as to what area in the visual field has been selected.

In the current experiments, observers searched for a singleton target among multiple nontargets and possibly one distractor. To investigate the relative contribution of stimulus-driven and goal-driven activity, we made the relative salience of target and distractor either similar within the orientation dimension (Experiments 1 and 2), dissimilar across dimensions (Experiment 3), or systematically varying within the orientation dimension (Experiment 4).

Experiment 1

Participants were required to make a speeded saccade toward a prespecified line segment tilted toward one direction, presented among multiple vertically oriented line segments. On half of the trials, an irrelevant distractor was presented. The distractor was a line segment tilted in the opposite direction from the target. Target and distractor were equally salient among the nontargets but maximally different in angle of orientation. Target and distractor were chosen to be equally salient to allow accurate estimation of the relative contribution of stimulus-driven and goal-driven control. If visual selection was initially completely stimulus driven, one would expect that fast eye movements particularly would be equally likely to be directed to the target and the distractor. If, however, stimulus-driven control was contingent on the goals and intentions of the observer, eye movements should always be directed toward the target.

Method

Participants. Eight students of the Vrije Universiteit Amsterdam participated as paid volunteers in a 50-min session. Participants ranged in age from 19 to 31 years, and all reported having normal or corrected-to-normal vision.

Apparatus. A Pentium II Dell computer with a 21-in. (53.34-cm) SVGA color monitor (Philips Brilliance 201 P) controlled the timing of the events and generated stimuli. Eye movements were recorded by means of an EyeLink tracker (SR Research Ltd., Mississauga, Ontario, Canada) with a 250-Hz temporal resolution and a 0.2° spatial resolution. The system uses an infrared video-based tracking technology to compute the pupil center and pupil size of both eyes. An infrared head-motion tracking system tracked head motion. Display resolution was $1,024 \times 768$ pixels. All participants were tested in a sound-attenuated, dimly lit room with their heads resting on a chinrest. The monitor was located at eye level 75 cm from the chinrest.

Stimuli. Participants performed a visual search task in which they were instructed to make a speeded saccade to a target. Half of the participants searched for a right-tilted target (i.e., a line segment tilted 45° to the right),

whereas the other half searched for a left-tilted target (i.e., a line segment tilted 45° to the left), among multiple nontargets (i.e., vertically oriented line segments). In half of the trials, one of the nontargets was replaced by an irrelevant distractor consisting of a line segment tilted 45° to the left if the target was right-tilted or of a line segment tilted 45° to the right if the target was left-tilted. Elements were arranged in a 9×13 rectangular matrix with a raster width of $17.06^\circ \times 12.63^\circ$. Targets and distractors could appear at six different locations. These six potential locations were placed on an imaginary circle in such a way that, embedded in the matrix of nontargets, targets and distractors were always presented at equal eccentricity from fixation (6.1° of visual angle). When a target and a distractor were presented, the circular angle between the two elements was always 120° (see Figure 1). Elements had an approximate height of 0.76° of visual angle and an approximate width of 0.31° of visual angle. Elements were white (Commission Internationale de l'Éclairage [CIE] x -, y -coordinates of .288, .316, respectively; 93.14 cd/m^2) and were presented on a black background.

A control study was carried out to ensure that the target line elements were perceived accurately from fixation point. Four participants were presented with one target (tilted 45° to the right or tilted 45° to the left) embedded in a matrix of nontargets (vertical line elements). Search displays were identical to those in Experiment 1 except that no distractor was presented. Participants were instructed to indicate, using a manual response, whether the target presented was tilted to the right or the left. Participants completed 120 trials. Participants were instructed not to make eye movements and to keep fixation at the fixation point. Trials in which an eye movement was made (6.8% of all trials) were excluded from the analysis. The results showed that in 97% of all trials, participants correctly responded to the orientation of the target line element. This demonstrates that elements were accurately perceived from fixation point.

Design and procedure. A within-subject design was used. Target and distractor orientations (i.e., a right-tilted target with a left-tilted distractor vs. a left-tilted target with a right-tilted distractor) were counterbalanced over participants. In each trial, a target and multiple nontargets were presented. In half of the trials, one of the nontargets was replaced by a distractor.

To start a trial, participants pressed the space bar, after which a fixation point was presented for 1,000 ms, followed by the stimulus array. The stimulus array was presented for 1,500 ms. Participants were instructed to remain fixated until the search display appeared. Then, they were instructed to make a speeded saccade to the target while maintaining a high level of accuracy. Participants were explicitly told to ignore the distractor if it was presented. After making an eye movement to the target, participants were instructed to remain fixated on the target until the search display disappeared. To make sure that participants understood the task correctly, participants were given a written instruction, followed by an oral instruction.

Participants first completed 24 practice trials. The experimental part consisted of 360 trials divided in two blocks of 180 trials each. Feedback concerning saccade latency was provided every 30 trials. Participants were

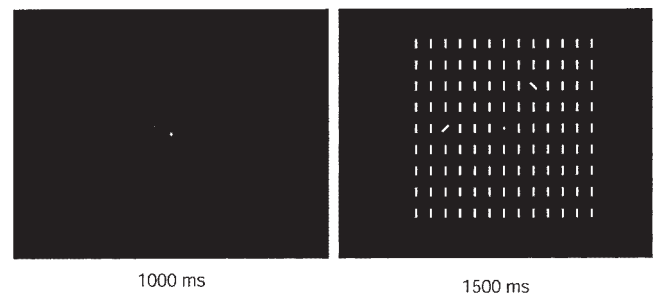


Figure 1. An example of the primary stimulus display.

free to take a break between the two experimental blocks. Prior to the recording, participants viewed a calibration display consisting of nine points that were fixated sequentially in a square array.

Results

Initial saccade latencies below 80 ms (anticipation errors; 2.2% of trials) and saccade latencies above 600 ms (0.9% of trials) were counted as errors and were excluded from the analyses. The initial saccade was assigned to a target or distractor if the endpoint of the initial saccade was within 3° of visual angle of the particular target or distractor position. Of the initial saccades, 1.9% missed the location of either the target or the distractor and were not analyzed further.

The initial saccade latencies toward the target were much shorter in the no-distractor trials ($M = 238$ ms) as compared with the distractor trials ($M = 280$ ms), $t(7) = 5.56$, $p < .01$. On distractor trials, 57% of the initial saccades were correctly directed toward the target, whereas 43% of the initial saccades were incorrectly directed toward the distractor. In general, more saccades were directed toward the target than toward the distractor, $t(7) = 4.82$, $p < .01$. On distractor trials, initial saccade latencies were shorter when the eyes were directed toward the distractor ($M = 254$ ms) than when the eyes were directed toward the target ($M = 280$ ms), $t(7) = 4.17$, $p < .01$. Of the total of incorrect eye movements directed toward the distractor, 65% continued to move toward the location of the target. The mean fixation duration at the location of the distractor was 236 ms.

To investigate the relative contribution of stimulus-driven and goal-driven control in visual selection as a function of time, we calculated, for the distractor trials, the mean saccade latencies and the proportions of correct saccades (i.e., saccades directed toward

the target) separately for each quintile of the individual saccade latency distributions (see Figure 2). Overall, saccades were equally likely to be directed to the target and distractor except in the fifth quintile. The slowest 20% of the saccades were more likely to be directed to the target than to the distractor, $t(7) = 6.44$, $p < .01$.

Discussion

Experiment 1 had two major results. First, the presence of an irrelevant distractor had a substantial effect on the proportion of correct saccades toward the target and the latencies of those saccades. The proportion of correct saccades toward the target was lower when a distractor was present than when the distractor was absent. Furthermore, the latency of saccades toward the target was higher when a distractor was present than when no distractor was present. These findings replicate those earlier obtained in other studies on saccadic target selection (Godijn & Theeuwes, 2002; Irwin et al., 2000; Theeuwes et al., 1998, 1999). It should be noted, though, that in contrast to previous studies, the current results were obtained with a static discontinuity, that is, the distractor was defined in the orientation domain. Oculomotor capture effects have previously been demonstrated primarily with dynamic discontinuities (but see Theeuwes, DeVries, & Godijn, 2003). The present results show that oculomotor capture also occurs when the distractor is defined in the orientation domain.

Second, if a distractor was present, differential results were obtained for the fastest and slowest saccades. Although fast eye movements were equally likely to be directed to either the target or the distractor, the slowest fifth of saccadic eye movements were more likely to be directed toward the target than toward the distractor.

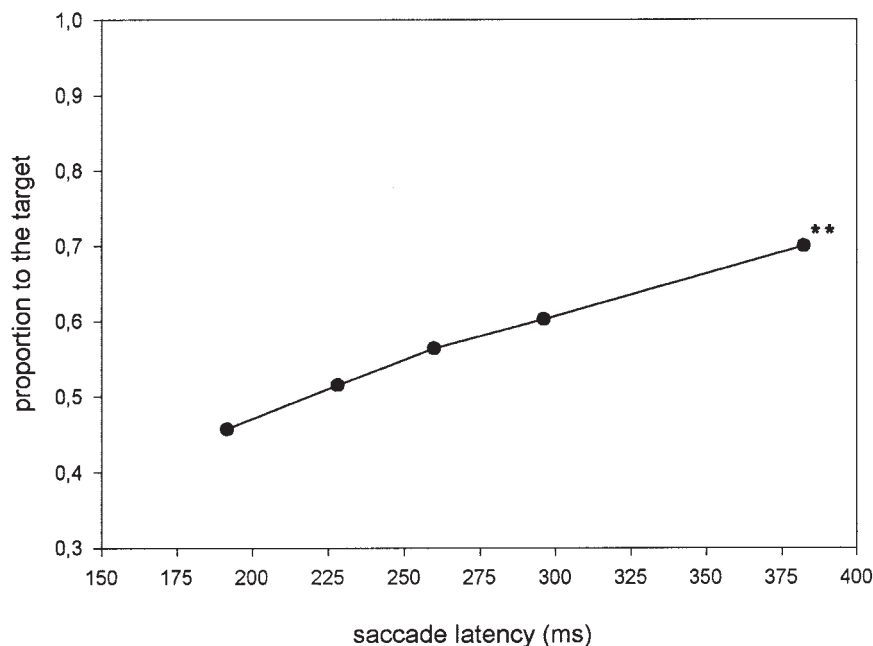


Figure 2. The proportion of saccades directed toward the target (tilted element) as a function of time. The distractor presented is tilted in the opposite direction from the target. ** $p < .01$; one-sample t test (test value = 0.5), two-tailed.

The results of Experiment 1 are in line with the notion that visual selection is initially completely stimulus driven. Apparently, early responses are controlled by stimulus salience only. Goal-driven control is possible only after some minimal time period has elapsed. These results are in line with both a bottom-up view and a timing account of visual selection.

It is important to note that even though the information required for a correct eye movement was available before an eye movement was made (see the results of our control study), the accuracy in Experiment 1 was quite low. This finding indicates that participants followed the speed instructions. Previous studies have shown that early stimulus-driven oculomotor capture can be observed only when participants are required to respond as fast as possible (Irwin et al., 2000; Kramer et al., 1999). Without speed stress, eye movements may become completely goal driven. Indeed, previous studies using the oculomotor capture paradigm have demonstrated that up to 40% of errors may occur with speed stress, whereas without speed stress, no erroneous eye movements to the irrelevant distractor have been observed (see, e.g., Theeuwes et al., 1999). The purpose of the present study was to examine both early and late mechanisms controlling visual selection.

The present findings are difficult to reconcile with a top-down view of visual selection. Even though observers were perfectly able to discriminate between the target and the distractor at central fixation (as demonstrated in the control study), their initial eye movements were equally distributed between the two singleton stimuli. If visual selection was contingent on the attentional control setting of an observer, initial eye movements should not have been equally likely to be directed toward the target and distractor. Indeed, according to the contingent capture model of Folk et al. (1992), observers should have been able to configure their visual system to selectively respond to task-relevant stimulus properties. The present results suggest that they were not able to do so: The presence of an irrelevant distractor had a profound effect on initial visual selectivity. Nevertheless, there are two ways in which the present results might also be accommodated by a top-down view of visual selection.

It is possible that the identities of the target and distractor in Experiment 1 were confused. As a consequence, early-in-time observers might have erroneously made a saccade toward the distractor because they falsely perceived the distractor as target. Target and distractor were mirror images and therefore highly confusable (see, e.g., Rollenhagen & Olson, 2000). It is possible that the initial confusion led to a high proportion of perceptual errors early on, suggesting that eye movements were stimulus driven during early processing, whereas in truth, they might have been completely goal driven (i.e., toward the falsely perceived distractor).

Alternatively, it might have been that observers were in an orientation singleton detection mode (Bacon & Egeth, 1994; Folk, Leber, & Egeth, 2002; Folk et al., 1992). Various authors have suggested that the use of a specific feature search mode might be more cognitively demanding than a singleton detection mode (Bacon & Egeth, 1994; Folk et al., 2002). The discrimination between the target and distractor in Experiment 1 required the use of a highly specific feature search mode to select the correct orientation value. Possibly, the attentional costs associated with such a highly specific setting might have been so high that observers adopted a much easier orientation singleton detection

mode. Indeed, recently, Folk et al. (2002) demonstrated that if observers searched for a specific color singleton target in a central letter stream, the presentation of an irrelevant color singleton distractor interfered regardless of its color value. Folk et al. suggested that observers were possibly adopting a dimensional set enabling them to detect any discontinuity in the color domain. It is possible that something similar occurred in Experiment 1. Observers might have used an orientation singleton set to detect any discontinuity in the orientation domain. Experiments 2 and 3 were designed to address these possibilities.

Experiment 2

The aim of Experiment 2 was to investigate the relative contribution of stimulus-driven and goal-driven control to the time course of visual selection while target-distractor confusability was kept to a minimum. Even though, in Experiment 1, target and distractor were maximally distinct in terms of their angular difference (i.e., 90°), one may argue that they were not necessarily perceived as such. More specifically, it is known that humans and animals readily confuse mirror images (Bornstein, Gross, & Wolf, 1978; Rollenhagen & Olson, 2000; Sutherland, 1960). The target and distractor presented in Experiment 1 were both laterally and vertically symmetric. Despite the results of the control study showing that observers were quite able to discriminate between target and distractor, one may argue that the poor initial performance found in Experiment 1 was not due to stimulus-driven selection but to erroneous goal-driven selection. To investigate this possibility, in Experiment 2, we removed the lateral and vertical symmetry between target and distractor. In Experiment 2, search displays were similar to those in Experiment 1 except that the individual search elements were rotated 45°. That is, half of the participants searched for a horizontal target among diagonal right-tilted nontargets, whereas the other half searched for a vertical target among the same nontarget stimuli. In half of the trials, one of the nontargets was replaced by an irrelevant distractor, a vertical line segment if the target's orientation was horizontal and a horizontal line segment if the target's orientation was vertical.

If visual selection was initially stimulus driven, fast saccades should be equally often directed toward the target and distractor. If visual selection was initially goal driven, performance would be expected to greatly improve relative to that in Experiment 1. That is, eye movement should have been uniformly directed toward the target.

Method

Participants. Nine students of the Vrije Universiteit Amsterdam participated as paid volunteers in a 50-min session. Participants ranged in age from 14 to 31 years, and all reported having normal or corrected-to-normal vision. One person was omitted from the analyses because of a too-poor fixation accuracy prior to the appearance of the search display (>30% of the trials), resulting in a total of 8 participants.

Apparatus. The apparatus was identical to that in Experiment 1.

Stimuli. The stimuli were identical to those of Experiment 1, except that all line elements were rotated 45° clockwise. Half of the participants searched for a horizontal target (90° of arc relative to the vertical), whereas the other half searched for a vertical target (0° of arc relative to the vertical). In half of the trials, one of the nontargets was replaced by an irrelevant distractor (a vertical line segment if the target was horizontal and

a horizontal line segment if the target was vertical). Target and distractors were presented among right-tilted nontargets ($+45^\circ$ of arc relative to the vertical).

Design and procedure. Design and procedure were the same as in Experiment 1.

Results

Initial saccade latencies below 80 ms (anticipation errors; 6.1% of trials) and saccade latencies above 600 ms (1.0% of trials) were counted as errors and were excluded from the analysis. The initial saccade was assigned to a target or distractor if the endpoint of the initial saccade was within 3° of visual angle of the particular target or distractor position. Of the initial saccades, 5.1% missed the location of either the target or the distractor and were not analyzed further.

The initial saccade latencies toward the target were shorter in the no-distractor trials ($M = 235$ ms) as compared with the distractor trials ($M = 266$ ms), $t(7) = 4.18$, $p < .01$. On distractor trials, 65% of all the initial saccades were correctly directed toward the target. More saccades were directed toward the target than toward the distractor, $t(7) = 3.73$, $p < .01$. On distractor trials, incorrect eye movements to the distractor were faster ($M = 225$ ms) than correct saccades toward the target ($M = 266$ ms), $t(7) = 4.36$, $p < .05$. Of the total of incorrect eye movements directed toward the distractor, 82% continued to move toward the location of the target. The fixation duration at the location of the distractor was 193 ms.

To investigate the relative contribution of stimulus-driven and goal-driven control in visual selection as a function of time, we calculated, for the distractor trials, the mean saccade latencies and the proportions of correct saccades (i.e., saccades directed toward the target) separately for each quintile of the individual saccade

latency distributions (see Figure 3). Saccades were equally likely to be directed to the target and distractor except in the fourth and fifth quintiles. The slowest 40% of the eye movements were more likely to be directed to the target than to the distractor: fourth quintile, $t(7) = 4.98$, $p < .01$, and fifth quintile, $t(7) = 8.22$, $p < .01$.

To compare performance between Experiments 1 and 2, we conducted an analysis of variance (ANOVA) on the proportions correct in the distractor trials with experiment (1 vs. 2) as a between-subjects factor and quintile (1–5) as a within-subjects factor. No effect of experiment was found, $F(1, 14) = 4.01$, $p > .05$. A main effect of quintile was found, $F(4, 56) = 17.23$, $p < .01$. No interaction was found, $F(4, 56) < 1$. A similar ANOVA on the mean saccade latencies revealed a comparable pattern of results. No effect of experiment was found, $F(1, 14) < 1$. A main effect of quintile was found, $F(4, 56) = 99.20$, $p < .01$. No interaction was found, $F(4, 56) < 1$. Finally, comparing the fixation duration on the distractor between Experiments 1 and 2, we conducted a t test for independent samples. No significant difference was found between the fixation duration in Experiment 1 ($M = 235$ ms) and Experiment 2 ($M = 193$ ms), $t(14) = 1.71$, $p > .05$. Overall performance in Experiment 2 was similar to that in Experiment 1.

Discussion

The results in Experiment 2 are essentially identical to those obtained in Experiment 1. During early processing, target and distractor were equally likely to be selected. Later on, target selection outnumbered distractor selection, suggesting an increasing contribution of goal-driven control. It is important to note that even though target and distractor were maximally dissimilar in

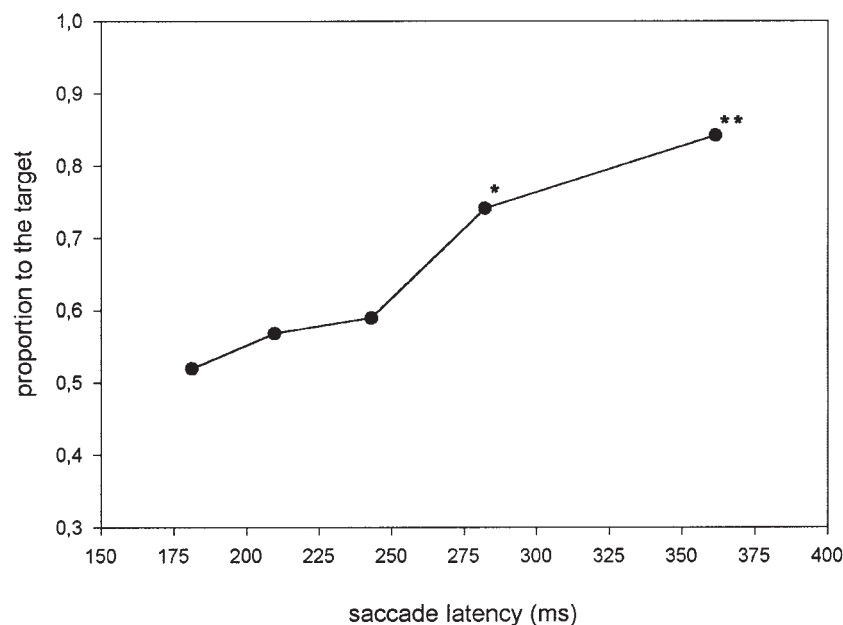


Figure 3. The proportion of saccades directed toward the target (horizontal or vertical line element) as a function of time. The distractor presented is rotated 90° relative to the orientation of the target. * $p < .05$; one-sample t test (test value = 0.5), two-tailed. ** $p < .01$; one-sample t test (test value = 0.5), two-tailed.

Experiment 2, performance was still very poor. Because target and distractor were maximally different from each other, it is rather unlikely that the initial poor performance was due to target–distractor confusability.

However, it remains possible that observers were voluntarily adopting an orientation singleton detection mode looking for a discrepancy in the orientation domain (Bacon & Egeth, 1994). To investigate this possibility, we executed a third experiment in which target and distractor were defined in different feature dimensions.

Experiment 3

Experiment 3 was a replication of Experiment 1 except that the distractor was defined by a unique feature in the color domain. Observers searched for a tilted line segment among multiple vertical line segments. On half of the trials, one nontarget was replaced by a vertical red distractor. Observers were explicitly instructed to search for the tilted target and informed that color was completely irrelevant.

Method

Participants. Twelve students of the Vrije Universiteit Amsterdam participated as paid volunteers in a 50-min session. Participants ranged in age from 22 to 31 years, and all reported having normal or corrected-to-normal vision.

Apparatus. The apparatus was identical to that in Experiment 1.

Stimuli. Except for the identity of the distractor, the stimuli were identical to those of Experiment 1. The distractor was a red vertical line (CIE x -, y -coordinates of .608, .346, respectively; 15.37 cd/m²). The orientation of the distractor was identical to that of the nontargets (0° of arc relative to the vertical). Half of the participants searched for a right-tilted target (i.e., a line segment tilted 45° to the right), whereas the other half searched for a left-tilted target (i.e., a line segment tilted 45° to the left), among multiple nontargets (i.e., vertically oriented line segments).

Design and procedure. Design and procedure were the same as in Experiment 1.

Results

Initial saccade latencies below 80 ms (anticipation errors; 6.2% of trials) and saccade latencies above 600 ms (0.2% of trials) were counted as errors and were excluded from the analysis. The initial saccade was assigned to a target or distractor if the endpoint of the initial saccade was within 3° of visual angle of the particular target or distractor position. Of the initial saccades, 2.1% missed the location of either the target or the distractor and were not analyzed further.

The initial saccade latencies toward the target were shorter in the no-distractor condition ($M = 207$ ms) as compared with the initial saccade latency toward the target when an additional distractor was presented ($M = 221$ ms), $t(11) = 4.71$, $p < .01$. On distractor trials, 65% of the initial saccades were correctly directed toward the target. More saccades were directed toward the target than toward the distractor, $t(11) = 3.11$, $p < .01$. On the distractor trials, initial saccade latencies were shorter when the eye was directed toward the distractor ($M = 183$ ms) than when the eye was directed toward the target ($M = 221$ ms), $t(11) = 7.21$, $p < .01$. Of the total of incorrect eye movements directed toward the distractor, 90% continued to move toward the location of the

target. The fixation duration at the location of the distractor was 119 ms.

To investigate the relative contribution of stimulus-driven and goal-driven control in visual selection as a function of time, we calculated, for the distractor trials, the mean saccade latencies and the proportions of correct saccades (i.e., saccades directed toward the target) separately for each quintile of the individual saccade latency distributions (see Figure 4). For the first quintile, saccades were more often directed toward the distractor than toward the target, $t(11) = 2.24$, $p < .05$. In this case, only 37% of the eye movements were correctly directed toward the target. Performance improved steadily with time. In the fifth quintile, that of the slowest eye movements, saccades were more often directed toward the target than toward the distractor, $t(11) = 8.38$, $p < .01$. In this quintile, 90% of all saccades were directed toward the target.

To compare the results obtained in Experiment 3 with those in Experiments 1 and 2, we conducted an ANOVA on the proportion correct in the distractor trials with experiment (1 and 2 vs. 3) as a between-subjects factor and quintile (1–5) as a within-subjects factor. No effect of experiment was found, $F(1, 18) < 1$. A significant interaction was found between experiment and quintile; the proportion correct increased more strongly as a function of quintile in Experiment 3 than in Experiments 1 and 2, $F(4, 72) = 3.84$, $p < .01$. A similar ANOVA on the saccade latencies showed that saccade latency was lower in Experiment 3 than in Experiments 1 and 2, $t(18) = 3.85$, $p < .01$. In addition, the increase in saccade latency as a function of quintile was less in Experiment 3 than in Experiments 1 and 2, $F(4, 72) = 13.03$, $p < .01$. Finally, fixation duration at the distractor was significantly shorter in Experiment 3 than in Experiments 1 and 2, $t(18) = 8.41$, $p < .01$.

Discussion

The results of Experiment 3 show that the presence of an irrelevant distractor defined in the color dimension had a significant effect on search performance. Furthermore, during early processing, observers tended to select the red distractor, whereas later on, they tended to select the target. Even though target and distractor were defined in different dimensions, observers were unable to ignore the distractor.

The results in Experiment 3 are very similar to those in Experiments 1 and 2. However, there are also some differences. In the first quintile, the proportion of correct eye movements is lower in Experiment 3 than in Experiments 1 and 2; in the final quintile, the proportion of correct eye movements is higher in Experiment 3 than in Experiments 1 and 2. Furthermore, saccade latencies are lower in Experiment 3 than in Experiments 1 and 2. Consequently, performance accuracy as a function of time increased more dramatically in Experiment 3 as compared with Experiments 1 and 2. These differences suggest that the moment at which goal-driven control becomes possible may vary depending on the specific target–distractor combination. It is possible that when target and distractor are defined within the same dimension, as was the case in Experiments 1 and 2, it takes longer for goal-driven control to become operational than when target and distractor are defined in different dimensions, as in Experiment 3. Moreover, the increase in performance as a function of time is greater in Experiment 3 than in Experiments 1 and 2. This suggests that the contribution of goal-driven control may also evolve faster if target and distractor

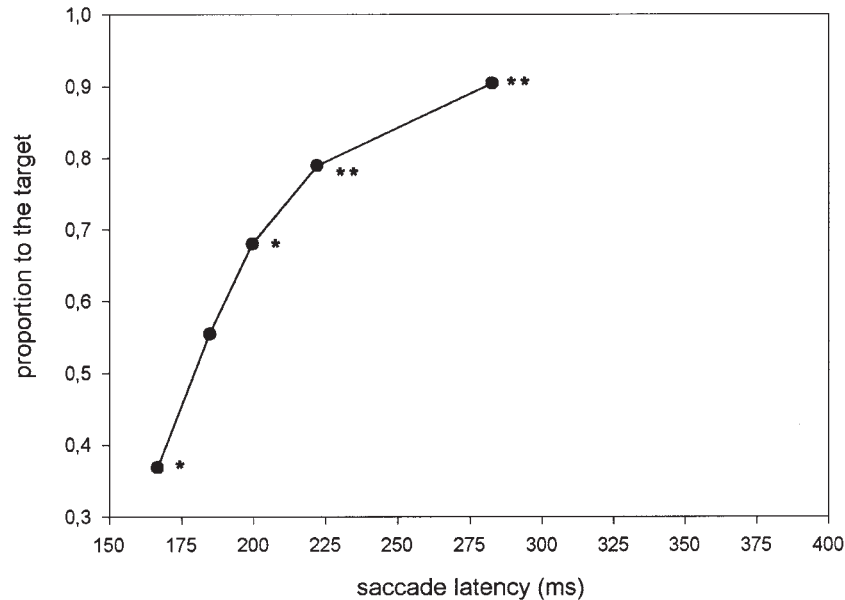


Figure 4. The proportion of saccades directed toward the target (tilted element) as a function of time. The distractor presented is a red vertical line element. * $p < .05$; one-sample t test (test value = 0.5), two-tailed. ** $p < .01$; one-sample t test (test value = 0.5), two-tailed.

are defined in different dimensions as compared with the same dimension.

Together, the results of Experiments 1–3 suggest that saccadic visual selection is initially completely data driven, whereas later selectivity appears to be goal driven. At this point, the question of how both types of control interact arises. Is goal-driven control contingent on stimulus-driven control, as suggested by a bottom-up view of visual selection, or do they operate completely independently from each other? In other words, does stimulus-driven control contribute to the ability to intentionally select a certain area in space, or are the effects of goal-driven control completely independent of stimulus-driven selection? The aim of Experiment 4 was to discriminate between these two possibilities.

Experiment 4

In Experiment 4, we examined the effects of distractor saliency on oculomotor behavior. Three types of distractors were used. Distractors presented were less salient than, equally as salient as, or more salient than the target, where saliency was taken as the amount by which an element's orientation differed from that of the nontargets. If goal-driven control was contingent on stimulus-driven control, as assumed by a bottom-up view of visual selection (Itti & Koch, 2000; Nothdurft, 2002; Theeuwes, 1991, 1992, 1994; Yantis & Hillstrom, 1994), it would be predicted that stimulus-driven detection of saliency should contribute to the ability to make use of goal-driven selection. In other words, distractor saliency would be expected to affect saccadic target selection irrespective of saccade latency. As a consequence, saliency effects should be present over all saccade latencies. In contrast, if visual selection was controlled by two independent processes, with stimulus-driven control operating early in time and goal-driven control operating later, it would be predicted that saliency effects

should only be present during early processing and should be absent during later processing.

Method

Participants. Fourteen students of the Vrije Universiteit Amsterdam participated as paid volunteers in a 70-min session. Participants ranged in age from 20 to 31 years, and all reported having normal or corrected-to-normal vision. Two people were omitted from the analysis because of poor fixation accuracy prior to the presentation of the search display (> 30% of the trials), resulting in a total of 12 participants.

Apparatus. The apparatus was identical to that in Experiment 1.

Stimuli. Experiment 4 was a replication of Experiment 1 with two major changes. First, instead of the distractor being present in 50% of the trials, it was present in every trial. Secondly, instead of one type of distractor being presented, three types of distractor were presented. Distractors were oriented at 22.5°, 45°, or 67.5°. Distractors were always rotated to the opposite direction from the target (see Figure 5). Participants were tested with only one type of target (+45° or -45°). Participants were tested with each of the three types of distractors (+/-22.5°, +/-45°, or +/-67.5°). Taking saliency as the amount by which an element's orientation differs from that of the nontargets, the saliency of the distractor was lowest when the distractor was oriented at 22.5°. The distractor was most salient when it was oriented at 67.5°.

Target	Distractors		
	22.5	45	67.5
+ 45	\	/	\
- 45	/	\	/

Figure 5. An overview of the three distractor types presented. Distractors were always rotated to the opposite direction from the target.

Design and procedure. The procedure was identical to that of Experiment 1. Target type was varied between participants such that half of the participants searched for a line tilted 45° to the right, whereas the other half search for a line tilted 45° to the left. Distractor type was varied between blocks of trials. Distractor type was counterbalanced across participants. Prior to the beginning of each block, participants were told about the identity of the distractor. For each distractor, each participant completed one practice block of 12 trials followed by one experimental block of 180 trials corresponding to each type of distractor. This resulted in a total of 540 experimental trials. Feedback concerning saccade latency was provided every 30 trials. Participants were free to take a break after completion of 180 trials.

Results

Initial saccade latencies below 80 ms (anticipation errors; 6.2% of trials) and saccade latencies above 600 ms (1.1% of trials) were counted as errors and were excluded from further analyses. The initial saccade was assigned to the target or distractor if the endpoint of the initial saccade was within 3° of visual angle of the particular target or distractor position. Of the initial saccades, 3.2% missed either the location of the target or that of the distractor and were not analyzed further.

Table 1 presents the percentages and the saccade latencies of the saccades directed toward the target or distractor for each condition. Paired-samples *t* tests showed that in the 22.5° distractor condition, significantly more initial saccades were directed toward the target as compared with the 45° distractor condition, $t(11) = 4.53, p < .01$. Significantly more initial saccades were directed toward the target in the 45° distractor condition than in the 67.5° distractor condition, $t(11) = 2.36, p < .05$.

In the 22.5° distractor condition, the initial saccade latency to the target ($M = 245$ ms) was equal to the initial saccade latency directed toward the distractor ($M = 255$ ms), $t(11) = 2.15, p > .05$. In the 45° distractor condition, the initial saccade latency directed toward the target was higher ($M = 267$ ms) as compared with when the saccade was directed toward the distractor ($M = 242$ ms), $t(11) = 4.34, p < .01$. A similar difference was found between the latencies directed to the target and distractor in the 67.5° distractor condition: Initial saccade latencies were higher when saccades were directed toward the target ($M = 268$ ms) than when saccades were directed toward the distractor ($M = 238$ ms), $t(11) = 4.11, p < .01$.

In the 22.5° distractor condition, 80% of the initial saccades directed incorrectly to the distractor continued their course toward the target. Fixation duration at the 22.5° distractor was 193 ms. In the 45° distractor condition, 73% of all initial saccades directed

toward the distractor continued to the target. Fixation duration at the 45° distractor was 194 ms. Of the total of incorrect eye movements directed toward the 67.5° distractor, 80% continued to move toward the location of the target. The fixation duration at the location of the 67.5° distractor was 188 ms.

To investigate the relative contribution of stimulus-driven and goal-driven control in visual selection as a function of time, we calculated, for each participant, the mean saccade latencies and the proportions of correct saccades (i.e., saccades directed toward the target) separately for each type of distractor and each quintile of the initial saccade latency distributions (see Figure 6). A within-subjects ANOVA was conducted on the proportions of correct saccades, with distractor type (22.5°, 45°, and 67.5°) and quintile (1–5) as main factors. A main effect of distractor type was found, $F(2, 22) = 22.72, p < .01$, as well as a main effect of quintile, $F(4, 44) = 5.30, p < .01$. An interaction between distractor type and quintile, $F(8, 88) = 9.01, p < .01$, indicated that the change in the proportion of correct eye movements as a function of quintile was different for the three types of distractors.

Separate ANOVAs were performed on the proportions of correct saccades for each distractor type, with quintile (1–5) as factor. In the 22.5° distractor condition, a main effect of quintile was found, $F(4, 44) = 3.29, p < .05$. Performance decreased as a function of quintile in the 22.5° distractor condition. In the 45° distractor condition, performance increased as a function of quintile, $F(4, 44) = 6.93, p < .01$. In the 67.5° distractor condition, performance also increased as a function of quintile, $F(4, 44) = 13.36, p < .01$.

Furthermore, separate ANOVAs were performed on the proportions of correct saccades for each quintile, with distractor type as factor. Significant differences were found in the first quintile, $F(2, 22) = 41.00, p < .01$; the second quintile, $F(2, 22) = 15.82, p < .01$; and the third quintile, $F(2, 22) = 5.40, p < .05$; but not in the fourth quintile, $F(2, 22) < 1$, nor in the fifth quintile, $F(2, 22) < 1$.

Finally, an ANOVA on the saccade latencies with distractor type and quintile as the factors showed only a significant effect of quintile, $F(4, 44) = 74.04, p < .01$. No effect of distractor type was found, $F(2, 22) < 1$. No interaction was found between distractor type and quintile, $F(8, 88) < 1$.

Discussion

The major result of Experiment 4 is that early in time, distractor saliency had a profound effect on oculomotor saccadic target selection performance, whereas no effect of distractor saliency was observed later in time.

The results of Experiment 4 argue against a bottom-up view of visual selection. If goal-driven control was contingent on stimulus-driven control, saliency effects should have been consistently present across the entire range of saccade latencies. The results show that this was not the case. Remarkable in this respect is the finding that even though initially saccadic target selection performance was very high when the target was the most salient element in the display (in the 22.5° distractor condition), saccadic target selection performance decreased as a function of saccade latency. Apparently, initial stimulus-driven activity does not contribute to goal-driven performance.

Table 1
Percentage and Saccade Latencies (in ms) of the Saccades Directed Toward the Target or Distractor in Experiment 4

Direction of eye movement	Orientation of distractor		
	22.5°	45°	67.5°
To the target			
Percentage	69.5%	58.4%	53.7%
Saccade latency (ms)	245	267	268
To the distractor			
Saccade latency (ms)	255	242	238

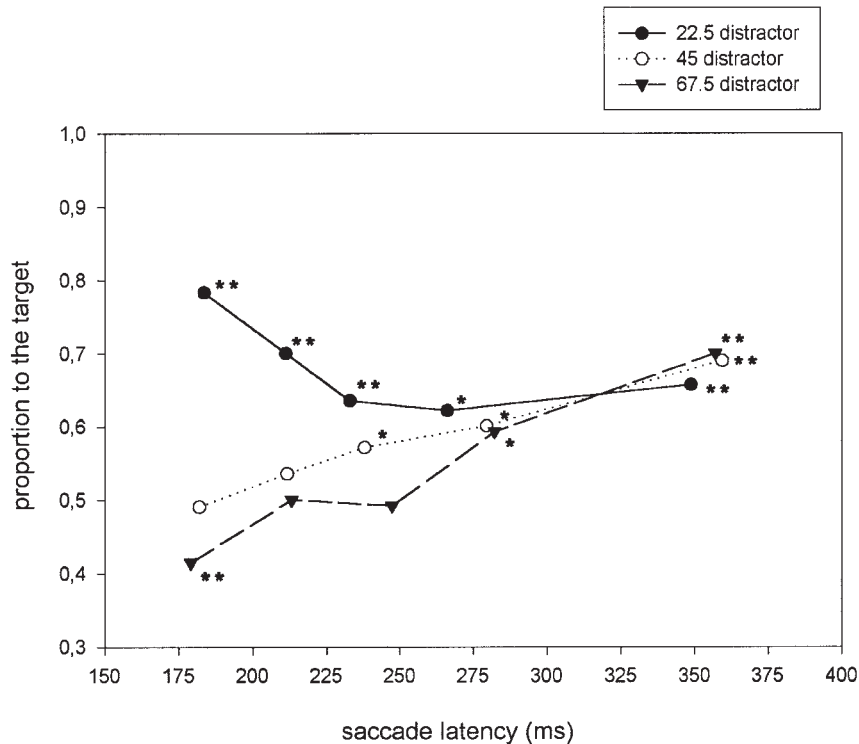


Figure 6. The percentage of saccades directed toward the target in the three conditions as a function of time. The distractors presented are rotated 22.5°, 45°, or 67.5° of arc relative to the vertical, in the opposite direction from the target. * $p < .05$; one-sample t test (test value = 0.5), two-tailed. ** $p < .01$; one-sample t test (test value = 0.5), two-tailed.

The results of Experiment 4 also argue against a top-down view of visual selection. Even though a blocked design was used, allowing observers to make maximal use of possible goal-settings (see Theeuwes & Burger, 1998), observers in a substantial proportion of trials could not prevent their eyes from being captured by the irrelevant distractor. These results suggest that participants were not able to be selective within the orientation domain. Alternatively, it is possible that observers chose not to be selective on a feature level. It is possible that in each condition, observers were prepared just to relax and let their eyes go to the most salient element in the display. If observers had used this strategy, that is, a singleton detection mode, performance should have been as predicted by a bottom-up account. However, as already outlined above, the data are not in line with this view. The results of Experiment 4 provide support for a timing account of visual selection assuming that selective control is ultimately the result of the operation of two distinct processes in different time windows.

General Discussion

The purpose of the present study was to investigate the role of stimulus-driven and goal-driven control in saccadic visual selection. Three alternatives regarding visual selection were examined: goal-driven control being contingent on stimulus-driven control, stimulus-driven control being contingent on goal-driven control, or both types of control independently operating in different time windows. Four experiments were performed to estimate the time

course of the relative contribution of stimulus-driven and goal-driven control to saccadic visual selection. The results of Experiments 1–4 uniformly demonstrate that whereas saccadic visual selection is initially completely stimulus driven, later in time, goal-driven control dominates visual selection. Moreover, initial stimulus-driven activity does not seem to contribute to the ability to voluntarily select a location in the visual field later in time.

The findings of the present study argue against a top-down view of visual selection. Even though participants knew the identity of the target and the distractor beforehand, they were unable to ignore the distractor in all four experiments. Moreover, Experiment 3 demonstrated that even if the distractor was defined in a dimension other than that of the target, the presence of the distractor, in particular when fast eye movements were made, substantially affected performance. These results render a top-down view of visual selection unlikely. Finally, in Experiment 4, a distractor was presented in 100% of the trials. Knowing that a distractor was presented in every trial should have prevented observers from using a singleton detection mode (Bacon & Egeth, 1994). In Experiment 4, to reach a higher level of accuracy, observers should perhaps have adopted a feature search mode. The results demonstrate that participants did not seem capable of doing so. It is important to note that Bacon and Egeth (1994) have claimed that even though goal-driven selectivity for a specific feature value is possible, observers do not necessarily make use of it. Moreover, the target was relatively salient in all of our experiments. Conse-

quently, one could argue that despite the absence of any incentive to do so, observers in the present study might have used a singleton detection mode instead of a feature search mode. However, if observers did use a singleton detection mode, then performance should have been as predicted by a bottom-up account. The results of Experiment 4 show that this was not the case; observers were not driven solely by saliency in target selection. Instead, saliency effects found early in saccadic selection disappeared when saccadic latency increased. That is, even though performance had not yet reached ceiling, saliency did not affect the slowest 40% of the saccades. In fact, only fast saccades benefited from target salience. Remarkable in this sense was the finding that when the target was more salient than the distractor (i.e., in the 22.5° distractor condition), performance even dropped with increasing saccade latency. These results demonstrate that when participants respond more slowly, they do not necessarily make fewer errors. In fact, performance may even decrease as saccade latency increases. Apparently, the speed-accuracy trade-off observed in Experiments 1–3 does not hold under all circumstances. In particular, if a target is more salient than a concurrently presented distractor, performance may even decline as responses become slower. When eye movements become slow, target salience does not contribute to visual selection. This latter finding strongly argues against the idea that visual selection is contingent on stimulus-driven control as advocated by a bottom-up view.

These results provide support for a timing account of visual selection. According to this perspective, visual selection may be either stimulus or goal driven as a product of response time. As in most current models of visual selection (Cave & Wolfe, 1990; Folk et al., 1992; Itti & Koch, 2000; Koch & Ullman, 1985; Theeuwes, 1991, 1992, 1994; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989), it is assumed that visual selection is the result of the output provided by some common salience map that combines input from different modules. The pattern of activity in this map may give rise to a single location that is most likely to be selected (Itti & Koch, 2000; Koch & Ullman, 1985). The data presented here provide new constraints for this theoretical salience map. We have shown that splitting the saccadic eye movements of observers on the basis of time reveals an evolution from initial dominance of stimulus-driven activity to later goal-driven activation. The salience map is assumed to be accessible at any point in time. That is, it is assumed that response mechanisms may gain access to the salience map both relatively early and relatively late, following the generation of an initial activity pattern (Tse, Sheinberg, & Logothetis, 2002). Depending on the time at which a response probes the salience map, visual selection appears to be completely stimulus driven or goal driven. Thus, if an observer responds on the basis of the activation pattern in the salience map relatively early in time, responses will be primarily stimulus driven. Later responses will become increasingly goal driven as determined by the declining contribution of stimulus-driven control and the increasing contribution of goal-driven control to the salience map.

Current psychological and neurophysiological evidence supports a timing account of visual selection. The notion that stimulus-driven control and goal-driven control operate in different time windows has been substantiated by many studies (Cheal & Lyon, 1991; Nakayama & Mackeben, 1989; Trappenberg, Dorris, Munoz, & Klein, 2001). In general, these studies have demonstrated that the effects of stimulus-driven control not only last a

shorter period but also come about faster than the effects of goal-driven control (see Godijn & Theeuwes, 2002). For example, in a study by Müller and Rabbit (1989), observers had to indicate the orientation of a *T* presented in one of four peripherally presented boxes. The presentation of the boxes was preceded by a valid or invalid peripheral or central location cue, and stimulus onset asynchrony between cue and search display was varied. The results demonstrated that facilitation and inhibition from peripheral and central cues were characteristically different. Although the effects of peripheral cues were fast and transient (< 175 ms), the effects of central cues were slow and sustained (> 400 ms). The results of this study suggest that stimulus-driven selection (as elicited by a peripheral cue) not only occurs at an earlier point in time than goal-driven selection (as elicited by a central cue) but also has a different time course (see Nakayama & Mackeben, 1989).

The notion that stimulus-driven and goal-driven influences independently arise and converge at a common site or representation where visual spatial selection ultimately takes place has been adopted by many major theories on visual selection (Cave & Wolfe, 1990; Kastner & Ungerleider, 2000; Treisman & Gelade, 1980; Treisman & Gormican, 1988; Wolfe, 1994; Wolfe et al., 1989). For example, in the guided search model (Cave & Wolfe, 1990; Wolfe, 1994; Wolfe et al., 1989), it is explicitly assumed that stimulus-driven and goal-driven activation sum up in a common location-specific activation map. The activation map is assumed to contain no information about the source (i.e., what) of activation but only about its location (i.e., where) in the visual field. The activation pattern in the map determines in what sequence an observer selects different locations in space. That is, attention is assumed to be allocated in the order of decreasing activity (Wolfe, 1994). Even though initial accounts of a common location or activation map were not inspired by the idea that there exists one single locus in the brain corresponding to it (a common map was proposed merely out of modeling convenience), recent neurophysiological evidence suggests that it might not be implausible to assume that this is the case.

For example, recently, Li (2002) suggested that the primary visual cortex (V1) may serve the purpose of a salience map. Several studies have suggested that even though cells in V1 are tuned to specific features (Hubel & Wiesel, 1968), their output in terms of salience might be equivalent (Li, 2002). In other words, V1 may signal the presence of salience irrespective of the specific feature or features that signal it (Itti & Koch, 2000; Li, 2002; Nothdurft, 2002). Apart from V1, the visual cortex contains more than 30 separate visual areas (Felleman & Van Essen, 1991) that receive inputs from V1 and have in turn reentrant connection with V1 (Bullier, McCourt, & Henry, 1988; Di Lollo, Enns, & Rensink, 2000; Hochstein & Ahissar, 2002). The activity of neurons in V1 can thus be modulated by the reentrant signals from higher extrastriate visual areas. As pointed out by Di Lollo et al. (2000), reentrant signals can reconfigure the initial activation pattern with the result that “the same cells can serve different functions at different stages of processing” (p. 501). It is possible that these reentrance signals deriving from extrastriate visual areas (as well as from parts of the frontal cortex) modulate the neural activity to fit the current goals of an observer (Kastner & Ungerleider, 2000). In this sense, initial stimulus-driven activity patterns in V1 may become increasingly more goal driven as more reentrance signals

have entered the map. Suggestions like these can be accommodated by a timing account of visual selection.

Other areas that may serve the purpose of a salience map are the frontal eye fields (Bichot & Schall, 1999; Bichot, Thompson, Chenthal Rao, & Schall, 2001; Schall & Hanes, 1993; Schall & Thompson, 1999), the lateral intraparietal area (Goldberg, Bisley, Powell, Gottlieb, & Kusunoki, 2002; Gottlieb, Kusunoki, & Goldberg, 1998; Kusunoki, Gottlieb, & Goldberg, 2000), and the superior colliculi (McPeck & Keller, 2001, 2002; Munoz, Dorris, Pare, & Everling, 2000; Trappenberg et al., 2001). These structures represent the locations of salient items without the feature selectivity. Moreover, these structures are modulated by the goals of the observer (see, e.g., Basso & Wurtz, 1997; Bichot & Schall, 1999; Dorris & Munoz, 1998; Platt & Glimcher, 1999) and are intimately linked to saccade programming (see, e.g., Munoz & Fecteau, 2002; Schall, 1995) and attention (see, e.g., Bichot & Schall, 1999; Colby & Goldberg, 1999; Schall, 2002). For example, Trappenberg et al. (2001) have developed a model of saccade initiation based on the competitive integration of exogenous and endogenous signals converging on the middle layers of the superior colliculi. The idea that stimulus-driven and goal-driven signals are integrated by dynamic competition (see also Godijn & Theeuwes, 2002) seems difficult to reconcile with the present timing notion. However, the two ideas may be reconciled if one assumes that stimulus-driven selection and goal-directed selection occur in separate time windows preventing eye movements from being simultaneously guided by stimulus-driven and goal-directed activations. Indeed, Trappenberg et al. proposed that exogenous and endogenous inputs differ not only in their latency but also in their time course. Cell recordings in the superior colliculus reveal a transient component closely following the appearance of an external stimulus. Trappenberg et al. assumed that after an initial rise, exogenously generated activation may decline shortly after presentation because of lateral inhibition within the saccade map. This would imply that at the time that endogenously generated activation arrives at the saccade map, exogenous activation has already decayed. As a consequence, slow eye movements would become completely independent of exogenous control. This idea is in strong accordance with the data presented in this article.

How does the timing notion proposed here relate to other theories on visual selection? As noted above, a top-down view of visual selection is fundamentally different from a timing view in the sense that the former explicitly assumes stimulus-driven activity to be contingent on goal-driven control, whereas the latter view assumes both processes to be independent. Nevertheless, both views bear some resemblance. Indeed, the timing notion may even be perceived as being consistent with the distinction between the singleton detection mode and the feature search mode, as proposed by Bacon and Egeth (1994). However, in contrast to the idea that observers may voluntarily choose to be engaged in one or the other mode, a timing notion assumes that the singleton detection mode is initially mandatory, possibly followed by a feature search mode (see also Lamy & Egeth, 2003).

The timing view also differs from current bottom-up notions of visual selection because no contingency is assumed between stimulus-driven and goal-driven selection. A bottom-up view of visual selection explicitly assumes goal-driven selection to be contingent on stimulus-driven selection. For example, Nothdurft (2002) proposed that there are two separate stages of processing:

The first stage is based on the output of a salience map that may guide the operation of a second identification stage (see also Sagi & Julesz, 1985). Because identification can be assumed to be a necessary prerequisite for various forms of goal-driven control, goal-driven control is necessarily assumed to be contingent on the efficiency of stimulus-driven processes. To provide evidence for this idea, Nothdurft showed that salient elements are not only detected more quickly but also identified faster than less salient elements. Even though Nothdurft's findings are in line with a bottom-up account, they do not necessarily conflict with a timing account. In Nothdurft's study, saliency information was explicitly task relevant. Apparently, if available, saliency can be used to accomplish rapid detection and identification. However, if task demands explicitly instruct observers to search for a certain identity (as in the present study), saliency may be beneficial only during a limited period of time. Under such conditions, it becomes evident that stimulus-driven activity is not a necessary prerequisite for goal-driven selection.

In conclusion, the present study provides evidence for the view that stimulus-driven selection and goal-driven selection occur at different points in time after the presentation of a stimulus display. This strongly argues for a timing view of visual selection according to which the relative contributions of stimulus-driven control and goal-driven control independently vary in time.

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Received January 7, 2003

Revision received February 16, 2004

Accepted February 19, 2004 ■



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