# Goal-driven modulation as a function of time in saccadic target selection

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Four experiments were performed to investigate the contribution of goal-driven modulation in saccadic target selection as a function of time. Observers were required to make an eye movement to a prespecified target that was concurrently presented with multiple nontargets and possibly one distractor. Target and distractor were defined in different dimensions (orientation dimension and colour dimension in Experiment 1), or were both defined in the same dimension (i.e., both defined in the orientation dimension in Experiment 2, or both defined in the colour dimension in Experiments 3 and 4). The identities of target and distractor were switched over conditions. Speed−accuracy functions were computed to examine the full time course of selection in each condition. There were three major results. First, the ability to exert goal-driven control increased as a function of response latency. Second, this ability depended on the specific target−distractor combination, yet was not a function of whether target and distractor were defined within or across dimensions. Third, goal-driven control was available earlier when target and distractor were dissimilar than when they were similar. It was concluded that the influence of goal-driven control in visual selection is not all or none, but is of a continuous nature.

*Keywords*: Dimensions; Eye movements; Goal-driven control; Time course; Visual selection.

While there is no question that visual selection may be guided by an observer's goals and intentions (e.g., Findlay, 1997; Folk, Remington, & Johnston, 1992; Kim & Cave, 1999; D. E. Williams & Reingold, 2001; L. G. Williams, 1967; Wolfe, Butcher, Lee, & Hyle, 2003), little is known about the dynamics of these goal-driven influences. In this article, speed−accuracy functions were used to evaluate the time-course of goal-driven saccadic selection. Time-course functions that measure the growth of accuracy over processing time provide conjoint assessments of discrimination (accuracy) and processing dynamics (speed; e.g., Dosher, 1979; Dosher, Han, & Lu, 2000; McElree & Carrasco, 1999; Schouten & Bekker, 1967; Wickelgren, 1977). Given that goal-driven control affects visual selection, the question is whether goal-driven selectivity is possible early on following, possibly even prior to, display presentation, or whether selectivity is only possible later, well after display presentation.

According to traditional models of visual selection, goal-driven control is assumed to be possible prior to attentional selection (Treisman & Sato,

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1990; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989; Wolfe & Horowitz, 2004). By this hypothesis, before attention is allocated to a given location, certain features or dimensions are set to receive priority over other features or dimensions. In contrast, others have argued that early selection cannot be affected by goal-driven processes. By this, goal-driven modulation may occur only after a minimum amount of time has elapsed following display presentation (Hochstein & Ahissar, 2002; Nothdurft, 2002; Sagi & Julesz, 1985; Theeuwes, 1992; van Zoest, Donk, & Theeuwes, 2004).

In line with the idea that modulation may occur prior to stimulus presentation, Müller and colleagues (Krummenacher, Müller, & Heller, 2001; Müller, Heller, & Ziegler, 1995; Müller & Krummenacher, 2006; Müller, Krummenacher, & Heller, 2004; Müller, Reimann, & Krummenacher, 2003) proposed a dimension-weighting account. Corresponding to this account, research has shown that goal-driven modulation varies depending on whether search is carried out for multiple features of the same dimension or multiple features of different dimensions (e.g., Found & Müller, 1996; Müller et al., 1995; Wolfe, 1994; Wolfe et al., 1989). According to Müller et al. one dimension may receive more attentional weight at the expense of another. If a target dimension is known in advance, signals from that dimension are amplified. In support of this account, it was shown that search for odd-one-out feature targets takes longer when the target can be present in one of several dimensions than when the target can be present in only one dimension. For example, Müller et al. required participants to respond to the presence or absence of an odd element in a search display. In the within-dimension condition, targets were all defined within the orientation dimension (left-tilted, horizontal, and right-tilted small grey bars among small grey vertical bars), while in the cross-dimension condition targets were defined across three different dimensions—that is, orientation, colour, and size (a right-tilted grey small bar, a vertical black small bar, or a grey vertical large bar among small grey vertical bars). The results showed that detection of the right-tilted target, the element that was present in

both conditions, was significantly slower in the cross-dimension condition than in the within-dimension condition. The authors suggested that this pattern resulted from an inability to establish weights in the cross-dimension condition due to the fact that the target could have been defined in any of a number of ways. With this in mind, Müller et al. concluded that the results supported the idea that dimensions were gated by goal-driven influences prior to the presentation of the display.

In contrast, others have suggested that goal-driven control needs time after the presentation of the search display to become effective (Hochstein & Ahissar, 2002; Nothdurft, 2002; Sagi & Julesz, 1985; Theeuwes, 1992; van Zoest et al., 2004). For example, van Zoest and Donk (2005) have shown that goal-driven control is not possible during early saccadic selection. Van Zoest and Donk (2005) required participants to make a saccade toward a predefined target presented concurrently with multiple nontargets and one distractor. The distractor was more salient, equally salient, or less salient than the target. The results showed that only when saccadic latencies were long were the eye movements directed in the manner dictated by the task instructions. Short-latency eye movements were completely stimulus driven, and no goal-driven control was possible. These results suggest that goal-driven control does not affect search immediately following the presentation of stimuli. Only after some amount of time has passed can goal-driven control selectively influence search (van Zoest et al., 2004).

Van Zoest et al. (2004) further showed that performance in a visual search task where an additional irrelevant distractor singleton was presented was better when the target and an irrelevant distractor were defined in different dimensions than when they were defined in the same dimension. In one experiment both target and distractor were defined within the orientation dimension. In another experiment, however, the target was an orientation singleton while the distractor item was a colour singleton, effectively defining the two stimuli in different dimensions. When saccadic performance was analysed as a function of

saccade latency, the results showed that in this latter situation performance reached a higher level earlier in time than when target and distractor were defined in the same dimension. The speed−accuracy functions observed in the two experiments were different, suggesting that the time-course of selection depends on the target−distractor relation. Van Zoest et al. (2004) suggested that when target and distractor are defined within a dimension, it may take longer for goal-driven control to become operational than if target and distractor are defined in different dimensions. These results suggest that goal-driven control evolves as a function of time and does so differently as a function of whether target and distractor were defined within or across dimensions.

Both Müller et al. (1995) and van Zoest et al. (2004) observed differences in performance as a function of whether targets and distractors were defined within or across dimension. However, the accounts offered to explain this finding by Müller et al. and van Zoest et al. differ, specifically on when in time these differences come about. In Müller et al. the differences observed are largely a function of instruction and the ability to set different weights prior to the presentation of the search display. In contrast, van Zoest et al. have argued that the results are due to differences in the time required before goal-driven information is available. To summarize, while some have argued that goal-driven modulation may occur immediately, as a function of instruction, others have argued that goal-driven modulation may only evolve after the presentation of a stimulus.

In the current work, the time-course of goal-driven control was investigated via the manipulation of experimental instructions and eye movement measurements. Participants were presented with similar search displays in different instruction conditions. Participants searched for one specific target singleton while simultaneously

an irrelevant distractor singleton was presented. The instructions were such that in one condition, one of the singletons was the target and the other singleton the distractor, while in the other condition the roles were reversed. As a result, it was possible to measure performance to identical singleton elements as a function of whether an element was defined as a target or distractor. Because the search displays presented were identical in both instruction conditions, the amount of stimulus-driven activation did not vary over conditions.[1] In other words, as instructions only defined whether the same stimulus was a target or distractor, goal-driven selectivity was assessed in terms of the relative proportion of first saccades directed towards a singleton depending on whether it was defined as a target or distractor. In order to investigate the time course of visual processing, analyses were performed separately for the short and long saccadic reaction times; it was examined whether the relative proportions of correct eye movements changed with saccade latency. If, for example, an equal number of eye movements were directed to a singleton regardless of experimental instructions, one may conclude that the selection of the singleton was entirely a product of stimulus-driven processes. If, in contrast, eye movements were, in line with the instructions, consistently made to the target-defined singleton, one may infer that eye movement selection was the product of goal-driven processes. Moreover, evidence for early goal-driven selectivity would be manifest when a difference in performance as a function of instruction is found for the short-latency responses. Evidence for late selectivity is supported when an effect of instruction is found only for the higher response latencies.

In the present study, target and distractor were defined in different dimensions (i.e., orientation and colour, in Experiment 1), or were both

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[1] In order to be able to make a prediction regarding the role of goal-driven control it is important that the manipulation concerning the instruction does not affect the relative saliency of a target or distractor in a display. As pointed out by Wolfe et al. (2003) it is rather difficult to independently manipulate goal-driven and bottom-up components. For example, increasing the heterogeneity of nontargets might reduce bottom-up saliency of a target, but also makes goal-driven specification of the target more difficult (however, see van Zoest & Donk, 2004; Wolfe et al., 2003).

defined in the same dimension (i.e., both defined in the orientation dimension in Experiment 2, or both defined in the colour dimension in Experiments 3 and 4). Depending on whether goal-driven modulation is present instantly at the beginning of a trial or evolves as a function of time, variations in performance are to be expected earlier or later in time as a function of whether target and distractor are defined within or across dimensions. Regardless, based on previous findings (Found & Müller, 1996; Müller et al., 1995; van Zoest & Donk, 2005), performance is expected to be better when target and distractor are defined across dimensions (i.e., Experiment 1) than when they are defined within dimensions (i.e., Experiment 2, 3, and 4).

## GENERAL METHOD

### Participants
In total 35 students of the Vrije Universiteit Amsterdam participated as paid volunteers in a single 105-minute session. The numbers of participants tested in each experiment were 8 (Experiment 1), 10 (Experiment 2), 9 (Experiment 3), and 8 (Experiment 4). In Experiment 2, 2 participants failed to act in accordance with the instructions and were omitted from further analysis. In Experiment 3, 1 participant failed to make an eye movement in on average one third of all trials and was discarded from further analysis, yielding a total of eight datasets in this experiment. Participants ranged in age from 18 to 30 years, and all reported normal or corrected-to-normal vision.

### Apparatus
A Pentium II Dell computer with a 21″ SVGA colour monitor (Philips Brillance 201 P) controlled the timing of the events and generated the stimuli. Eye movements were recorded by means of an Eyelink tracker (SR Research Ltd.) with a 250-Hz temporal resolution and a gaze resolution (noise limited) of $<0.01°$ and a gaze position accuracy of $<0.5°$. The system uses an infrared video-based tracking technology to compute the pupil centre and pupil size of both eyes. An infrared

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.
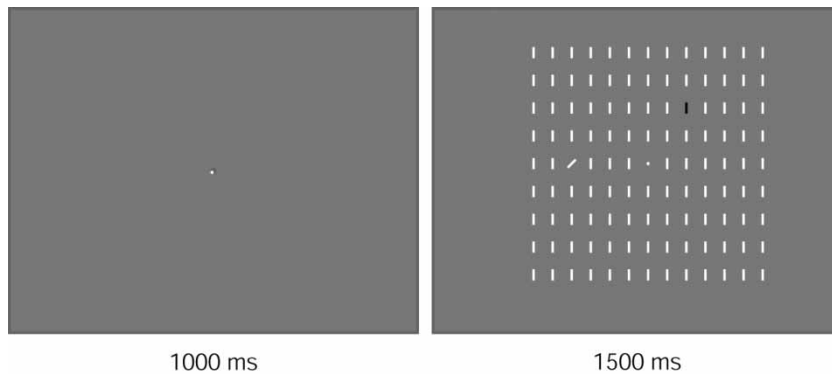
### Stimuli
Targets were presented among multiple nontargets (i.e., vertically oriented white line segments, CIE $x$, $y$ coordinates of .288/.316; 93.14 cd/m$^2$) and were defined either by orientation or by colour. In Experiment 1, in half of the trials, one of the nontargets was replaced by an irrelevant distractor, defined either by orientation or by colour. In Experiments 2−4, the distractor was presented in every trial. Stimuli were presented on a black background (see Figure 1).

Elements were arranged in a $9 \times 13$ rectangular matrix with a raster height of $17.06°$ and width of $12.63°$. 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 the fixation point. When a target and a distractor were presented the circular angular distance between the two elements was always $120°$. Elements had an approximate height of $0.76°$ of visual angle and approximate width of $0.31°$ visual angle.

### Design and procedure
A within-subject design was used. Participants completed two blocks, and each block had its own instruction. The singleton defined as target in the first block was defined as a distractor in the second block, whereas the singleton defined as distractor in the first block was defined as target in the second block. Block order was counterbalanced across participants.

To start a trial, participants pressed the spacebar on a standard computer keyboard. Trial sequence was as follows: A fixation point was presented for 1,000 ms, followed by the stimulus array for 1,500 ms. Participants were instructed to remain fixated until the search display appeared,

| 1000 ms | 1500 ms |

Figure 1. *The primary stimulus display. This example is modified such that the colour singleton is represented by the black line element presented on a grey background. In Experiments 1–4, the background presented was black. In Experiment 1, an orientation singleton and a red colour singleton were presented.*

at which point they were instructed to make a saccade to the target. Participants were instructed to make this saccade as quickly as possible following the presentation of the display, and they were explicitly instructed to ignore the distractor if it was presented and to maintain a high a level of accuracy in saccadic selection. After making an eye movement to the target, participants were instructed to remain fixated on the target until the search display disappeared. To ensure that participants fully understood the task both verbal and written instructions were provided.

In Experiments 1 and 3, each block was composed of 312 trials, and participants completed 36 practice trials before beginning each of the two blocks. A short break was provided halfway through each block (after 156 trials), and participants were required to take a 15-minute break between blocks. Feedback concerning saccade latency was provided every 26 trials. In Experiments 2 and 4, each block consisted of 300 trials; a break was taken following 150 trials, and feedback regarding saccadic latency was provided every 25 trials. Calibration of the eye-tracking equipment was conducted prior to recording.

### Data 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. Initial saccades that missed both the target and distractor were not analysed further. Initial saccade latencies below 80 ms were regarded as anticipation errors and were excluded from further analyses. Saccade latencies above 600 ms were considered too slow and were not analysed further.

Mean percentage of eye movements correctly directed to the target, and saccadic latencies of target- or distractor-directed saccades were compared in repeated measures analyses of variance (ANOVAs) or in Student's $t$ tests for paired samples. In order to examine performance as a function of time more closely, the time course of the percentage of eye movements directed to the target in the distractor-present condition was analysed separately in each block. For each participant, an individual distribution of the initial saccade latencies was calculated irrespective of the saccade destination, and this distribution was separated into five quintiles, each of which contained an equal number of trials (five bins each containing 20% of responses). For each quintile the percentage of initial eye movements directed to the target, as well as the average saccadic latency, was calculated.

Further, for each quintile, the difference was calculated between the percentage of eye movements towards a certain singleton when it was defined as target and when it was a distractor. As this

difference is defined by instruction, these scores provide a direct estimate of the extent to which observers were able to exert goal-driven control. For each difference score in a quintile, a *t* test of means was performed against a constant value 0.0, where 0.0 implies no difference in performance as a function of whether the singleton was defined as target or distractor. A *t* test of means was also performed against a constant value of 100, where a 100 implies that performance as a function of whether the singleton was defined as target or distractor was maximally different.

## EXPERIMENT 1

In one block of trials participants were instructed to make an eye movement to the orientation singleton, while in the other block of trials participants were instructed to make an eye movement to the red colour singleton. On half of the trials an irrelevant distractor was presented. The distractor was a red vertical line element if the target was a white right-tilted element and a white right-tilted element if the target was a red vertical line element. The contrast of most interest in Experiment 1 is between the two distractor-present conditions (i.e., red target with orientation distractor, and orientation target with red distractor) as in these conditions the displays were identical across instruction conditions. Therefore, any difference observed in performance to a given singleton as a function of instruction effectively represented the degree to which goal-driven control was possible.

### Method

#### Stimuli
The orientation singleton was a white line segment tilted 45° to the right (CIE *x, y* coordinates of .288/.316; 93.14 cd/m²), and the colour singleton was a vertical red line (CIE *x, y* coordinates of .608/.346; 15.37 cd/m²).

### Results

The mean percentage of excluded trials in Experiment 1 is plotted in Table 1. Block order

Table 1. *The percentage of trials excluded from the analysis in Experiments 1–4*

| Experiment | Anticipation errors[a] | Saccade latency > 600 | Saccades missed target or distractor |
|---|---|---|---|
| 1 | 6.5 | 0.3 | 8.1 |
| 2 | 2.2 | 0.5 | 4.5 |
| 3 | 2.2 | 0.1 | 2.6 |
| 4 | 6.2 | 0.5 | 7.3 |

[a]Latency < 80 ms.

did not affect the overall percentage of eye movements directed to the target, $F(1, 6) < 1$, $MSE = 305.3$. Furthermore, block order did not affect the saccade latencies directed to the target in the no-distractor condition, $F(1, 6) = 3.74$, $MSE = 372.6$; it did however affect the saccadic latencies to the target in the distractor-present condition, $F(1, 6) = 7.42$, $MSE = 341.2$, $p > .05$, such that observers were slower to select the target in the second block. However, most importantly, none of the interactions reached significance. As a result, further analyses were conducted on data collapsed across blocks.

Table 2 presents the percentages and the saccade latencies of the saccades directed towards the target or distractor for each instruction condition. Significantly more correct eye movements were directed toward the target in the colour instruction condition than in the orientation instruction condition, $t(7) = 5.46$, $p < .01$. A 2 × 2 ANOVA on saccadic latency to the target was performed with condition (colour and orientation instruction) and distractor presence (absent and present) as factors. A main effect of condition was found, $F(1, 7) = 13.46$, $p < .01$, as well as a main effect of distractor presence, $F(1, 7) = 21.07$, $p < .01$. Saccadic latencies were shorter in the colour instruction condition than in the orientation instruction condition and were shorter in the distractor-absent condition than in the distractor-present condition. The interaction between condition and distractor presence was nearly significant, $F(1, 7) = 5.29$, $p = .055$, suggesting that the effect of distractor presence was greater in the orientation instruction

Table 2. *Percentage and saccade latencies of the saccades directed towards the target or distractor in Experiment 1*

| Direction of eye movement | Distractor-absent condition | Distractor-present condition | | Defined as distractor |
| | To the target, saccade latency | Defined as target | | Saccade latency |
| | | Percentage | Saccade latency | |
|---|---|---|---|---|
| Orientation singleton | 194 | 62.0 | 206 | 180 |
| Colour singleton | 179 | 97.1 | 188 | 168 |

*Note:* Latencies in ms.

condition than in the colour instruction condition. Nevertheless, the presence of the orientation singleton distractor had also a significant effect on the saccadic latencies in the colour instruction condition, $t(7) = 3.43$, $p < .05$.

The time-course of performance is plotted in Panel A of Figure 2. An ANOVA was performed on condition (colour and orientation instruction) and bins (5) as factors. A main effect of condition was found $F(1, 7) = 30.23$, $MSE = 806.6$, $p < .001$. In addition, performance as a function of bin was significantly different in the two conditions, $F(4, 28) = 11.37$, $MSE = 183.2$, $p < .0001$. Linear contrasts showed that performance in the colour instruction condition did not significantly change as a function of saccade latency, $F(1, 7) < 1$, $MSE = 49.0$. In contrast, performance in the orientation instruction condition did significantly change with saccade latency, $F(1, 7) = 51.81$, $MSE = 310.3$, $p < .0001$. Accuracy in the orientation instruction condition was very low when selection occurred early. In fact, performance in the first three bins was not significantly different from chance in the orientation instruction condition (all $p > .05$). Post hoc comparisons (Tukey HSD) revealed that performance in the colour instruction and orientation instruction conditions was significantly different in all but the last two bins (Bin 1–3, all $p < .05$). At the longest saccade latencies, observers were equally well able to select the colour target and the orientation target.

Difference scores are depicted in Figure 3. Significant differences were found from a difference score of 0.0 starting in the first quintile, $t(7) = 23.47$, $p < .05$, implying that even the 20% shortest latency eye movements were affected by instruction. Perfect performance was found only in the last quintile, $t(7) = 2.01$, $p > .05$. In the 20% slowest trials participants discriminated the target from distractor without problems.

## Discussion

Experiment 1 had three major results. First, large differences were found in performance in the two conditions (i.e., colour instruction and orientation instruction condition). This was the case in both the distractor-absent and distractor-present condition. When no distractor was present, observers were significantly faster in making a correct eye movement to the colour target than to the orientation target. Furthermore, when a distractor was present, the percentage of eye movements correctly directed to the target was much higher in the colour instruction condition than in the orientation instruction condition. These results suggest that the colour singleton was more salient than the orientation singleton (e.g., Theeuwes, 1992).
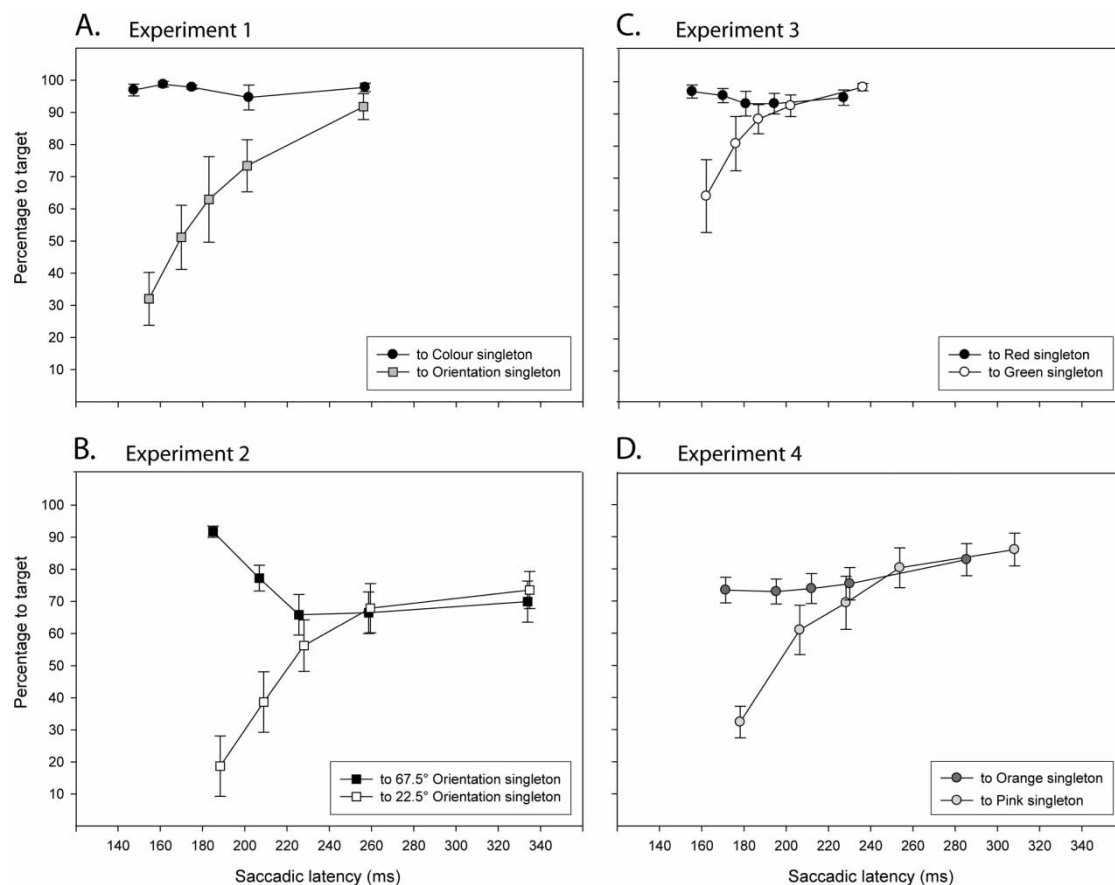
**Figure 2.** *The percentage of saccades directed to the target in each instruction condition for Experiments 1–4. (A) In Experiment 1, the target was an orientation singleton in one block and a colour singleton in the other block. (B) In Experiment 2, the target was a salient orientation singleton tilted − 67.5° to the left in one block and a nonsalient orientation singleton titled + 22.5° to the right in the other block. (C) In Experiment 3, the target was a red colour singleton in one block and a green colour singleton in the other block. (D) The target was a pink colour singleton in one block and an orange colour singleton in the other block in Experiment 4. The error bars represent standard error of the mean.*

Second, performance increased as a function of saccade latency in the orientation instruction condition, but not in the colour instruction condition. When saccadic latency was short, people were better able to correctly make an eye movement towards the colour target than the orientation target. These results are in line with the idea that the colour singleton was more salient than the orientation singleton, making it easier for participants to select the red target than the orientation target on the basis of saliency-driven

activity only (Nothdurft, 2006; Theeuwes, 1992; Yantis, 2005). Previous research has demonstrated that effects of stimulus salience are most apparent when stimulus selection occurs early following stimulus presentation, and that stimulus salience does not influence search when selection occurs late (van Zoest & Donk, 2005). Indeed, the speed–accuracy functions observed in both instruction conditions converged at long saccadic latencies. When saccade latency was long, people were equally well able to make an eye movement
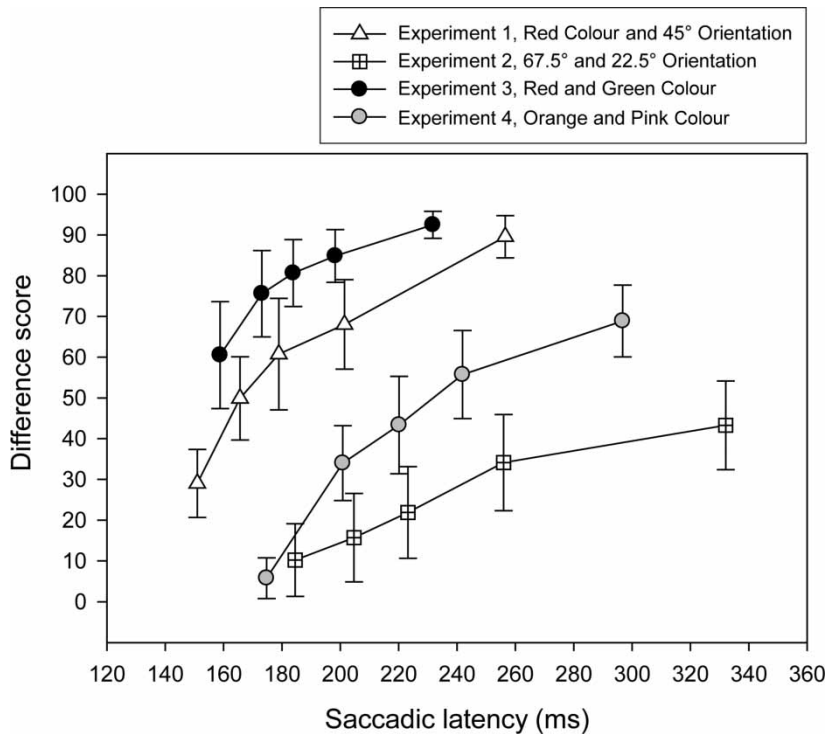
**Figure 3.** *For Experiments 1–4, the difference scores of an orientation or colour singleton that was presented as a target in one block and as a distractor in another block. Difference score = percentage (singleton defined as target) − percentage (singleton defined as distractor). The error bars represent standard error of the mean.*

towards the colour and orientation target. This convergence suggests that the effects of relative saliency decreased with saccade latency and were absent in the highest bin. The results of Experiment 1 are in line with these earlier findings in that differences between the two instruction conditions were only observed for short-latency saccades following display presentation (van Zoest & Donk, 2005, 2006).

Third, the results show that the contribution of goal-driven control to saccadic target selection increases with saccadic latency. Whereas limited goal-driven selectivity was observed for the short-latency saccades, long-latency saccades were completely goal driven (Cheal & Lyon, 1991; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989; van Zoest et al., 2004; Yantis & Jonides, 1990). These results show that when target and distractor

are defined in different dimensions, eye movement behaviour is subject to varying amounts of goal-driven influences. The extent to which eye movements are goal driven strongly depends on the time elapsed since the presentation of the search displays.

Even though the results of Experiment 1 show that the influence of goal-driven control strongly increases as a function of saccade latency, it is important to note that even the shortest latency saccadic responses were affected by instruction. In other words, when target and distractor are defined in different dimensions, goal-driven modulation, even though limited, is possible early in time (Treisman & Sato, 1990; Wolfe et al., 1989; Wolfe & Horowitz, 2004). We next investigated how goal-driven modulation evolves when target and distractor are defined within the same dimension.

Experiment 2 was designed to test saccadic competition between two elements defined in the orientation dimension.

## EXPERIMENT 2

Participants were required to make a saccade towards a prespecified diagonal line segment of one orientation (target) presented amongst multiple vertically oriented line segments and one diagonal line segment of another orientation (distractor). Similar to Experiment 1, target and distractor switched roles over instruction conditions. Furthermore, similarly to the singletons defined across dimensions in Experiment 1, both orientation singletons differed in their relative saliency.

## Method

### Stimuli
One singleton was rotated $-67.5°$ to the left, and the other singleton was rotated $+22.5°$ to the right; the items were tilted in opposite directions. The singletons were presented among multiple vertical nontargets. The $-67.5°$ tilted line segment stands out from the vertical oriented nontargets and is referred to as the salient orientation singleton. The $+22.5°$ line segment does not stand out from the vertical nontargets and is referred to as the nonsalient orientation singleton. All

elements were white line segments (CIE $x, y$ coordinates of .288/.316; 93.14 cd/m$^2$).

## Results

The mean percentage of excluded trials in Experiments 2 is plotted in Table 1. Block order did not affect performance: There was no significant difference between the percentages directed to the two types of target (tilted $-67.5°$ or $+22.5°$) as a function of block order, $F(1, 6) < 1$, $MSE = 393.72$, nor between the saccade latencies directed to the two target types as a function of block order, $F(1, 6) < 1$, $MSE = 7,180$. No interactions reached significance. As a result, further analyses were conducted on data collapsed over block order.

Table 3 presents the percentages and the saccade latencies of the saccades directed towards the target or distractor in each instruction condition. A significant difference was found between the percentages directed to the two types of target (tilted $-67.5°$ or $+22.5°$) as a function of instruction, $t(7) = 3.75$, $p < .005$, and between the saccade latencies directed to the two target types as a function of instruction, $t(7) = 3.85$, $p < .005$. Participants directed significantly more correct eye movements to the $-67.5°$ target (mean 74.2%) than to the $+22.5°$ target (mean 50.8 %). Participants were also faster to move correctly to the $-67.5°$ target (mean

Table 3. *Percentage and saccade latencies of the saccades directed towards the target or distractor in Experiments 2, 3, and 4*

| Experiment | Direction of eye movement | Defined as target | | Defined as distractor |
|---|---|---|---|---|
| | | *Percentage* | *Saccade latency* | *Saccade latency* |
| 2 | $-67.5$ | 74.2 | 240 | 220 |
| | $+22.5$ | 50.8 | 265 | 245 |
| 3 | red | 94.4 | 186 | 166 |
| | green | 84.4 | 196 | 165 |
| 4 | orange | 75.6 | 221 | 201 |
| | pink | 65.8 | 248 | 206 |

*Note:* Saccade latencies in ms.

240 ms) than to the +22.5° target (mean 265 ms). Furthermore, incorrect eye movements directed to the distractor were faster in the +22.5° target instruction condition (to the −67.5° distractor, mean 220 ms) than in the −67.5° target condition (to the +22.5° distractor, mean 245 ms), $t(7) = 4.52, p < .005$.

Performance as a function of time is plotted in Panel B of Figure 2. An ANOVA was performed on condition (−67.5° or +22.5° instruction condition) and bins (5) as factors. A main effect of condition was found, $F(1, 7) = 13.72, MSE = 774, p < .01$. In addition, performance as a function of time was significantly different in the two instruction conditions, $F(4, 28) = 24.20, MSE = 174.5, p < .0001$. Linear contrasts showed that performance in the −67.5° instruction condition significantly changed as a function of saccade latency, $F(1, 7) = 9.08, MSE = 259, p < .05$. Performance decreased as a function of time. Performance in the nonsalient +22.5° instruction condition also significantly changed with saccade latency, $F(1, 7) = 52.61, MSE = 295, p < .0005$. Accuracy for the +22.5° orientation target was very low when selection occurred early. In fact, in the first quintile, performance was significantly below chance, as supported by $t$ test of means again value 50, $t(7) = 3.33, p < .05$; performance in the second and third quintile was not significantly different from chance (both $p > .05$). Post hoc comparisons (Tukey HSD) revealed that performance in the −67.5° or +22.5° orientation instruction conditions was significantly different in all but the last three bins (Bin 1−2, all $p < .001$). At the longest saccade latencies, observers were equally well able to select the −67.5° and +22.5° orientation target.

Difference scores between performance to a singleton defined as target and distractor are plotted in Figure 3. No significant differences were found from 0.0 in the first quintile, $t(7) = 1.15, p > 0.1$. Significant differences were found in quintiles 4 and 5, the slowest 40% of eye movements (all $p < .05$). A $t$ test of means with constant value 100 showed that in no case was performance maximal. Performance across all quintiles in Experiment 2 was significantly different from perfect.

## Discussion

The results of Experiment 2 were similar to those obtained in Experiment 1. There were three main results. First, overall performance was better in the −67.5° instruction condition than in the +22.5° instruction condition, suggesting that indeed the −67.5° singleton was more salient than the +22.5° singleton. Second, performance increased as a function of saccade latency in the +22.5° instruction condition but decreased in the −67.5° instruction condition. However, no difference in performance between the two instruction conditions was found when saccadic latencies were long. When observers were slow to respond, they were equally well able to select the salient as well as the nonsalient orientation target. The convergence of both functions suggests that the effects of relative saliency decreased with saccade latency and were absent in the highest bins. In other words, similar to the results of Experiment 1, the results of Experiment 2 showed that the effects of the target salience were apparent only for the short-latency responses and were absent for all long-latency responses. Third, the contribution of goal-driven control increased with saccade latency. Short-latency saccades were unaffected by instruction whereas long-latency saccades were completely goal driven. These results are also similar to those obtained in Experiment 1 and in line with the view that goal-driven control evolves as a function of time following the presentation of the search display (Cheal & Lyon, 1991; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989; van Zoest et al., 2004; Yantis & Jonides, 1990). However, in contrast to the results obtained in Experiment 1, the results in Experiment 2 show that goal-driven selectivity was not possible when people were quick to select a target. Short-latency eye movements were not modulated by goal-driven control as evident from the differences scores depicted in Figure 3. Only for the longer saccade latencies were participants able to correctly distinguish the target from the distractor and were able to correctly make eye movements to the target. Nevertheless, performance was never perfect, even

in those cases where saccadic latencies were very long (>350 ms). Overall accuracy was substantially lower in Experiment 2 than in Experiment 1.

The difference in overall level of performance between Experiments 1 and 2 can be explained in at least three ways. First, and in line with previous research, it may be that a distractor defined in the same dimension as the target hampers search to a greater extent than a distractor defined in another dimension (e.g., Müller et al., 1995; van Zoest et al., 2004). In Experiment 2 the target and distractor were defined in the same dimension; whereas in Experiment 1 target and distractor were defined across dimension. In Experiment 1 observers may have been able to set different weights in line with the prespecified target dimension speeding up target selection in the process. In other words, because it is not possible to set these weights for features within a dimension, the additional processing time that is required to identity features of elements that are defined in the same dimension may be reflected in lower overall performance and a slower increase in the speed−accuracy function in Experiment 2.

Second, superior performance in Experiment 1 may be due to the presence of colour features. Previous research suggests that colour is special (Found & Müller, 1996; Motter & Belky, 1998; Olivers & Humphreys, 2003; D. E. Williams & Reingold, 2001; L. G. Williams, 1967). More specifically, results of earlier studies suggest that the colour features are available earlier for goal-driven selection than are orientation features (e.g., Motter & Belky, 1998). For example, D. E. Williams and Reingold (2001) required participants to search for a prespecified target in a triple conjunction search task, where stimuli varied in colour, shape, and orientation. Their results showed that participants were significantly more likely to direct their eye movements to distractors sharing target colour than to distractors sharing target shape or target orientation. D. E. Williams and Reingold suggested that colour information from the periphery is available to guide search earlier than does shape information

(Findlay, 1997; Findlay & Gilchrist, 1998). It may have been the case that in Experiment 1, elements defined in the colour dimension may have been selected quicker when they were a target and rejected quicker when they were a distractor. The presence of colour features may allow for more efficient search.

Third, the difference between performance in Experiments 1 and 2 may be the result of a difference in relative target−distractor similarity. Many studies have demonstrated that target−distractor similarity greatly affects search performance (Duncan & Humphreys, 1989, 1992). As such, a target or distractor may be identified as being a target or distractor much more readily when the target and distractor do not look similar. It could be argued that the degree of similarity between the orientation singleton and the red colour singleton in Experiment 1 was much smaller than the similarity between the two orientation singletons in Experiment 2. In turn, given that search efficiency increases with decreased target−distractor similarity (Duncan & Humphreys, 1989, 1992), the availability of goal-driven modulation as a function of time may crucially depend on target−distractor similarity. Goal-driven modulation may be in place much more readily when target and distractor are not similar, explaining the superior performance in Experiment 1 compared to Experiment 2. Thus, instead of relying on a dimension-weighting account or a view that grants a special role for the dimension colour, target−distractor similarity may best explain the present pattern of results.

Experiment 3 was designed, first of all, to test between the first two alternatives: Testing whether saccadic selection performance is explained best on the basis of whether elements are defined within or across dimensions or whether regardless of dimension, performance is best accounted for depending on whether the targets and distractors are defined by colour or not. In Experiment 3 the target and distractor were both defined in the colour dimension. Whereas the colours tested in Experiment 3 did not look similar, another set of colours was tested in Experiment 4 that did look

similar. Experiment 4 was thus conducted in order to test to what extent target–distractor similarity explains the current results.

## EXPERIMENTS 3 AND 4

In Experiment 3 the target and distractor were either a red colour singleton or a green colour singleton. According to the first hypothesis, if target identification is indeed slower when the target competes with a distractor that is defined in the same dimension, it is predicted that when a target and an irrelevant distractor are both defined in the colour dimension, one should find a substantial decrease in performance relative to the performance in a search task where target and distractor are defined in different dimensions. In this case, performance in Experiment 3 is expected to be similar to the performance observed in Experiment 2. According to the second hypothesis, if colour is special, and features of the colour dimension can be accepted or rejected quicker than features of other dimensions, the level of performance in Experiment 3 is expected to be better than performance in Experiment 2, where both elements were defined in the orientation dimension.

In Experiment 4 the target and distractor were again both defined in the colour dimension and were either a pink or an orange colour singleton. The colours pink and orange were similar and therefore much more difficult to discriminate than the colours red and green presented in Experiment 3. If colour as such is special, and goal-driven modulation occurs immediately upon display presentation for all searches in which a target and distractor are defined in the colour dimension, it is predicted that performance in Experiment 4 will be identical to performance in Experiment 3. On the other hand, if target–distractor similarity ultimately determines the speed and accuracy of goal-driven modulation, it is predicted that the speed–accuracy function in Experiment 4 will be substantially lower than the observed function in Experiment 3.

## Method

### Stimuli

In Experiment 3, the target was a red vertical line (CIE $x$, $y$ coordinates of .608/.346; 15.37 cd/m$^2$) or a green vertical line (CIE $x$, $y$ coordinates of .300/.599; 14.85 cd/m$^2$). In Experiment 4 the target and distractor identities were a pink vertical line (CIE $x$, $y$ coordinates of .424/.0566; 26.23 cd/m$^2$) or an orange vertical line (CIE $x$, $y$ coordinates of .472/.429; 26.70 cd/m$^2$). The colours red and green in Experiment 3 and the colours pink and orange in Experiment 4 were approximately matched for perceived luminance.

In both Experiments 3 and 4 the orientations of the target and distractor were identical to those of the nontargets ($0°$ of arc relative to the vertical). Nontarget stimuli were vertical white line segments (CIE $x$, $y$ coordinates of .288/.316; 93.14 cd/m$^2$).

## Results

Block order did not affect the overall percentage of eye movements directed to the red or green tilted target in Experiment 3, $F(1, 6) < 1$, $MSE = 301.7$, nor did block order affect the overall saccade latencies directed to the red or green target, $F(1, 6) < 1$, $MSE = 775.9$, nor to the red or green distractor, $F(1, 6) < 1$, $MSE = 3,601.3$. No interactions reached significance.

In Experiment 4, block order did not affect the overall percentage of eye movements directed to the pink or orange tilted target, $F(1, 6) = 2.40$, $MSE = 241.5$, $p > .1$, nor did block order affect the overall saccade latencies directed to the pink or orange target, $F(1, 6) < 1$, $MSE = 6,490$. However, a significant interaction was found between the saccade latency to the pink or orange target and block order, $F(1, 6) = 17.25$, $MSE = 98.3$ $p < .01$. No other interactions reached significance.

Table 3 presents the percentages and the saccade latencies of the saccades directed towards the target and distractor in each instruction condition in Experiment 3 and Experiment 4. In Experiment 3, a significant difference was found between the percentages directed to the two types

of target (red or green target) as a function of instruction, $t(7) = 3.15$, $p < .05$, and between the saccade latencies directed to the two target types as a function of instruction, $t(7) = 4.06$, $p < .01$. Participants directed significantly more correct eye movements to the red target (mean 94.4 %) than to the green target (mean 84.4 %). Participants were also faster to correctly move to the red target (mean 186 ms) than to the green target (mean 196 ms). However, no significant difference was found between the saccade latencies directed incorrectly to the distractors, $t(7) < 1$.

In Experiment 4, the difference between the percentages directed to the two types of target (pink or orange target) as a function of instruction was nearly significant, $t(7) = 2.28$, $p = .056$; a significant difference was found between the saccade latencies directed to the two target types as a function of instruction, $t(7) = 3.01$, $p < .05$. Participants directed more correct eye movements to the orange target (mean 75.7 %) than to the pink target (mean 65.8 %). Participants were significantly faster to correctly move their eyes to the orange target (mean 221 ms) than to the pink target (mean 248 ms). However, no significant difference was found between the saccade latencies of incorrectly directed eye movements (i.e., those to the distractor), $t(7) = 1.47$, $p > .1$

Performance in the red and green instruction conditions (Experiment 3) was plotted as a function of time (see Panel C of Figure 2). Significant differences were found between the conditions as a function of bin, $F(4, 28) = 8.93$, $MSE = 92.2$, $p < .001$. Linear contrasts revealed that performance in the red instruction condition significantly decreased as a function of time, $F(1, 7) = 5.72$, $MSE = 5.52$, $p < .05$. In contrast, performance in the green instruction condition significantly increased as a function of saccade latency, $F(1, 7) = 9.32$, $MSE = 543.7$, $p < .05$.

Performance in the pink and orange target conditions (Experiment 4) was plotted as a function of time (see Panel D of Figure 2). The percentage of eye movements correctly directed to the target in the orange instruction condition was higher than the percentage correctly directed to the target in the pink instruction condition; however,

the difference was not quite significant, $F(1, 7) = 5.16$, $MSE = 376.7$, $p = .06$. Significant differences were found between the conditions as a function of bin, $F(4, 28) = 14.66$, $MSE = 95.2$, $p < .0001$. Linear contrasts revealed that performance in the orange instruction condition did not significantly change as a function of bin, $F(1, 7) = 2.71$, $p > .1$. In contrast, performance in the pink instruction condition significantly increased as a function of saccade latency, $F(1, 7) = 54.94$, $p < .001$.

Difference scores between the correct eye movements and incorrect eye movements directed to the target and distractor for a colour singleton (i.e., red or green in Experiment 3, and orange and pink in Experiment 4) were calculated for each quintile (see Figure 3). Results showed that in all quintiles in Experiment 3 differences were found in performance as a function of whether the singleton was defined as a target or distractor (all $p < .01$). In all except the first quintile was performance not significantly different from perfect.

In Experiment 4, no significant differences were found from 0.0 in the first quintile, $t(7) = 1.16$, $p > .1$. Significant differences were found in second through to the fifth quintile (all $p < .05$). A $t$ test of means with constant value 100 showed that in no case was performance maximal. Performance across all quintiles in Experiment 4 was significantly different from perfect.

## Discussion

Experiment 3 had three major results. First, overall performance was better in the red instruction condition than in the green instruction condition. Apparently, the red target presented among the white nontargets was more salient that the green target among the white nontargets. Second, performance increased as a function of saccade latency in the green instruction condition but decreased in the red instruction condition. The two accuracy-functions converged when saccadic latency was long. The results suggest that, similar to the results of Experiment 1 and 2, the effects of relative saliency decreased as a function

saccade latency. The effect of target saliency was absent in the highest bins. Third, as illustrated in Figure 3, the contribution of goal-driven control increased with saccade latency. However, unlike the results of Experiment 2, goal-driven modulation was available early following the presentation of the search display. Even in the quickest responses, the initial percentage of eye movements directed to a colour singleton depended on whether this singleton was defined as a target or a distractor. The results of Experiment 3 suggest that goal-driven selectivity is possible instantaneously upon presentation of the search display when discrimination is required between two colours. However, similar to the results of the previous two experiments, target selectivity was not perfect when saccade latency was short. The extent to which eye movements are goal driven strongly depends on the time elapsed since the presentation of the search displays. Whereas goal-driven modulation was limited for the short-latency eye movements, long-latency eye movements were completely goal driven.

Experiment 4 had three major results. First, overall performance was better in the orange instruction condition than in the pink instruction condition, suggesting that the orange singleton presented among white nontargets was more salient than the pink singleton presented among white nontargets. Second, performance increased as a function of saccade latency in the pink instruction condition but not in the orange instruction condition. Moreover, the two speed−accuracy functions converged as a function of saccade latency. Observers were equally well able to select the pink and the orange target when saccade latency was long. This pattern of results suggests that the effects of relative saliency decreased with saccade latency and were absent in the highest bins. Third, the contribution of goal-driven control increased with saccade latency. Short-latency saccades were unaffected by instruction whereas long-latency saccades were directed in line with the instruction. The results of Experiment 4 show that the extent to which eye movements are goal driven strongly depends on the time elapsed since the presentation of the

search displays. Short-latency eye movements were not affected by instruction, whereas long-latency eye movements were. However, in contrast to the results of Experiment 3, performance in Experiment 4 never reached ceiling.

The results of Experiment 3 showed that participants were very well able to distinguish a target from a distractor when both were defined in the colour dimension. The results of Experiment 3 are not in line with the idea that search involving elements that are defined across dimension is easier than search involving elements that are defined within a dimension (e.g., Müller et al., 1995; van Zoest et al., 2004). The target and distractor in Experiment 3 were both defined within one dimension (the colour dimension); however, performance reached a higher level earlier in time in Experiment 3 than in Experiment 1, where the target and distractor were defined across dimensions (i.e., orientation and colour). The results of Experiment 3 contradict results that suggest that goal-driven control may be available earlier in time in when a target and distractor are defined across dimension than when they are defined within the same dimension (van Zoest et al., 2004). Search performance in the first three experiments was unrelated to whether or not target and distractor were unique within the same or different feature dimension (Found & Müller, 1996; Müller et al., 1995).

The results of Experiment 3 suggest that colour is special (Found & Müller, 1996; Motter & Belky, 1998; Olivers & Humphreys, 2003; D. E. Williams & Reingold, 2001; L. G. Williams, 1967). Accordingly, target and distractors defined in the colour dimension can be selected and rejected much more quickly than targets and distractors defined in another dimension. However, the finding that goal-driven modulation is established most rapidly when target and distractor are defined in different colours does not necessarily imply that colour is special. Indeed, the results of Experiment 4 suggest that target−distractor similarity greatly affects the speed and accuracy of goal-driven modulation. In line with previous research, target−distractor similarity significantly influenced saccadic target selection (Duncan,

1995; Duncan & Humphreys, 1989). The results showed that when target–distractor discrimination was made more difficult, overall performance dropped substantially in comparison to performance in Experiment 3 where colour discrimination was easy (red vs. green). Moreover, unlike the results of Experiment 3, the results of Experiment 4 showed that when discrimination was difficult, early goal-driven modulation was no longer possible. The results of the current experiment suggest that early goal-driven modulation is not guaranteed when a discrimination is made between elements that are defined by colour. When colour discrimination is made more difficult, performance evolves more comparably to when elements are defined in the dimension orientation.

## GENERAL DISCUSSION

The purpose of the present study was to investigate goal-driven modulation in saccadic selection as a function of time. Four experiments were performed; target and distractor identity was varied between dimensions (Experiment 1) and within dimensions (orientation in Experiment 2, and colour in Experiments 3 and 4).

Our results show that the effects of saliency were large early during processing while no effects of saliency were found later during processing. These results are in line with previous work (van Zoest & Donk, 2005; van Zoest et al., 2004). Moreover, a decrease in performance was found when the target was highly salient in Experiment 2 ($-67.5°$ orientation condition) and Experiment 3 (red target condition). When the target happened to be the most salient singleton in the display observers became increasingly less well able to correctly make a saccade towards the target with increasing response latency. These data suggest that stimulus salience may only be transiently represented (see for similar results, van Zoest & Donk, 2005; van Zoest et al., 2004). This might be due to fast passive decay of stimulus saliency information after the presentation of a stimulus array (Cheal & Lyon, 1991; Nakayama & Mackeben, 1989; Nothdurft, 2002; Yantis & Jonides, 1990) or

active inhibition of saliency-related activity to allow performance to be in line with the instructions (e.g., Godijn & Theeuwes, 2002; McSorley, Haggard, & Walker, 2006; Tipper, Howard, & Houghton, 2000). Both the idea of passive decay of stimulus salience and the idea of active inhibition of saliency signals may explain why the effects of stimulus-driven control decline as a function of time. The results of the current study are not conclusive to this matter, and further studies may provide insight in this finding.

The finding that goal-driven modulation evolves as a function of time following the presentation of the search display (see also, Ludwig & Gilchrist, 2002, 2003a, 2003b; McSorley et al., 2006) is difficult to reconcile with views arguing that observers may gate the selection process prior to the actual presentation of the search display (Bacon & Egeth, 1994; Folk et al., 1992; Müller et al., 1995; Wolfe, 1994). For instance, Folk et al. (1992) assume that visual selection is continuously influenced by the observers' attentional control settings. More specifically, according to their contingent involuntary orienting hypothesis, every form of visual selection is assumed to be modulated by the observer's prior goal settings. The present results are not in line with this assumption. While performance in each of the four experiments was affected by the observers' goal setting, goal-driven modulation was not invariably available. More specifically, in two experiments (Experiments 2 and 4), short-latency eye movements were completely unaffected by the observers' goal settings. In all four experiments, the influence of an observer's goal settings increased as a function of time since the presentation of a search display. These results suggest that only after the search display is presented is the sequence of processing modulated according to goal-driven settings: Goal-driven control takes time to become operational after the presentation of a search display (Cheal & Lyon, 1991; Hochstein & Ahissar, 2002; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Nothdurft, 2002; Sagi & Julesz, 1985; Theeuwes, 1992; van Zoest et al., 2004; Yantis & Jonides, 1990).

This conclusion is supported by the observed saccadic latencies of eye movements directed to distractors. A very consistent finding in the present study is that distractor-directed saccades to a given singleton have shorter latencies than correctly target-directed saccades to that very same singleton (see also, Godijn & Theeuwes, 2002; Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999; van Zoest et al., 2004). This is explained by the idea that distractor-directed saccades are purely stimulus driven, whereas target-directed saccades involve both a stimulus-driven and a goal-driven component. Given that goal-driven control comes on line later in time, the average latencies for target-directed saccades tend to be slower than those for distractor-directed saccades.

Furthermore, the results of Experiments 1–4 suggest that depending on the specific target–distractor combination goal-driven control was available earlier or later in time. The results are not in line with the idea that search efficiency is a function of whether a target and distractor were defined within or across dimensions (Found & Müller, 1996; Müller et al., 1995; van Zoest et al., 2004). Müller and colleagues proposed that if target and distractor are defined in different dimensions, the target dimension may receive more attentional weight at the expense of the distractor dimension. Accordingly, it is assumed that dimensional weighting is not possible when target and distractor are defined within the same dimension. As a result, goal-driven control is predicted to have a greater effect when target and distractor are defined in different dimensions than when they are defined in the same dimension. The results obtained in the present study do not support the idea of dimensional weighting (Krummenacher, Müller, & Heller, 2002; Müller et al., 1995; Müller & Krummenacher, 2006; Müller et al., 2004). Regardless of whether the target and distractor were defined within or across dimensions, goal-driven control varied with saccade latency. The increase of goal-driven modulation as a function of time was related to the similarity of the target and distractor. When target and distractor were dissimilar like in Experiment 3, goal-driven selectivity was readily available as evident from the large

contribution of goal-driven control in short-latency saccades. However, when target and distractor were similar, like in Experiment 4, short-latency saccades were unaffected by instruction, and goal-driven control only affected the medium- and long-latency saccades.

Nevertheless, our results demonstrate that independently of target–distractor similarity, the increase in goal-driven modulation as a function of time is larger when target and distractor are both defined within the colour dimension than when both are defined within the orientation dimension. When the similarity between colours was made more difficult in Experiment 4, overall performance in the former was still better than that in Experiment 2 (see Figure 3). These results are in line with other studies that have also found that search and discrimination of colour happen earlier and allow for more effective guidance than do searches and discrimination in shape or orientation (e.g., Motter & Belky, 1998). For example, D. E. Williams and Reingold (2001) showed that participants were more likely to fixate on distractors sharing target colour following short initial latencies than following long initial latencies. In contrast, the proportion of saccades directed to distractors sharing target shape were greater following long latencies than following short latencies. Evidence from previous studies support the idea that goal-driven guidance for features defined by orientation is not per se possible in cases of early selection (see also, Joseph, Chun, & Nakayama, 1997). The ability to selectively guide attention based on orientation information seems to be possible only later in time.

To conclude, traditional views on attentional selection (Treisman & Gelade, 1980; Treisman & Sato, 1990; Wolfe, 1994; Wolfe et al., 1989) generally do not take into account the dynamic aspects of selection control mechanisms. The results of the present study show that goal-driven modulation is not all-or-none in nature. Goal-driven control was seen to vary depending on the moment in time a response was probed (Tse, Sheinberg, & Logothetis, 2002; van Zoest & Donk, 2005; van Zoest et al., 2004).

Moreover, the amount of goal-driven modulation available was seen to vary as a function of specific target–distractor combination (Duncan & Humphreys, 1989, 1992; D. E. Williams & Reingold, 2001). Overall, our results suggest that the degree of goal-driven influence on visual selection is defined on a continuum.

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