The impact of predictive cues and visual working memory on dynamic oculomotor selection

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Strategic use of advanced information about search display properties can benefit covert attentional selection. However, little work has investigated this benefit on overt selection. The present study examined how cued information impacts oculomotor selection over time and the role played by individual differences in visual working memory (VWM) capacity in utilizing such cues. Participants searched for a specific orientation target in a saccade localization search task. Prior to each trial, additional information regarding secondary display features (color singleton identity) was either provided by a word cue or not. The cue increased accuracy performance from the earliest saccadic responses. VWM capacity was measured via a change-detection task and results showed that individuals’ VWM capacity scores were associated with cue impact, whereby participants with higher capacity derived an increased cue performance benefit. These findings suggest that strategic use of cue information to select and reject salient singletons can develop very early following display presentation and is related to an individual’s VWM capacity. This research indicates that stimulus-driven and goal-directed processes are not simply additive in oculomotor selection, but instead exhibit a distinct and dynamic profile of interaction.

Introduction

We are constantly inundated by sensory information, which competes for selection from limited-capacity attentional resources. However, the ability to efficiently and effectively select those subsets of information, which are most behaviorally relevant at any given time, can vary markedly between individuals. Most models of attentional control consider oculomotor and visual selection to be determined by the interplay between goal-directed processes, representing current observer selection goals, and stimulus-driven processes determined by the physical salience of elements in the visual environment (e.g., Bundesen, 1998; Desimone & Duncan, 1995; Eggeth & Yantis, 1997; Folk, Remington, & Johnston, 1992; Itti & Koch, 2000; Treisman & Sato, 1990; Wolfe, 1994, 2007; but see Awh, Belopolsky, & Theeuwes, 2012). By extension, saccades (i.e., rapid eye movements) used for oculomotor selection are generally considered to result from the combination of stimulus-driven and goal-directed processes (e.g., Godijn & Theeuwes, 2002). Although it is accepted that goal-directed strategies can use advanced information about the properties of a search display to directly influence covert attentional selection, relatively little work has investigated this benefit on overt saccadic selection. The aim of the present study was twofold: first, to explore how the impact of advanced knowledge provided by a preceding cue develops over time to influence oculomotor selection and second, to investigate the role that individual differences play in utilizing this cue to benefit selection performance.

The first focus of the present study specifically concerned the impact of nonspatial (cf. spatial) information provided by endogenous (cf. exogenous) cues, that is, those cues which require the information to be used in a goal-directed manner to assist selection. While previous research demonstrates that knowing what features to expect can improve visual search performance (Müller, Reimann, & Krummenacher,
the developmental time-course by which this influence operates to guide selection remains unclear. Given sufficient time to apprehend the cue, some research would indicate that advanced nonspatial information should have an immediate or early influence on attentional selection (Adams & Chambers, 2012; Bravo & Nakayama, 1992; Hillstrom, 2000; Lamy, Carmel, Egeth, & Leber, 2006; Lamy & Yashar, 2008; Leonard & Egeth, 2008; Müller & Krummenacher, 2006; Müller et al., 2003; Treisman, 1988; Wolfe, Butcher, Lee, & Hyle, 2003; Zhang & Luck, 2009), while other findings would suggest an influence only later, following initial stimulus-driven selection processes (Cave & Pashler, 1995; Hochstein & Ahissar, 2002; Kim & Cave, 2001; Nothdurft, 2002; Theeuwes, Reimann, & Mortier, 2006; Theeuwes & Van der Burg, 2007, 2011; Tsal & Lavie, 1988; van Zoest, Donk, & Theeuwes, 2004). In addition, more recently, it has been increasingly argued that many findings supporting a role for early goal-directed guidance by nonspatial information can also be explained by passive bottom-up intertrial priming (see Awh et al., 2012; Lamy & Kristjansson, 2013; Theeuwes, 2013, for recent reviews). For example, repeating versus switching a target dimension or feature value across trials can also lead to significant improvement in terms of speed and accuracy of visual selection, a phenomenon termed priming of pop-out (PoP) (Maljkovic & Nakayama, 1994). In paradigms where advanced knowledge of target properties is manipulated by holding properties constant (“blocked”) versus varying them (“mixed”) across trials, any evidence that attentional settings for a specific target feature can guide attention then becomes confounded with intertrial repetition effects (e.g., Belopolsky, Schreij, & Theeuwes, 2010; Maljkovic & Nakayama, 1994; Pinto, Olivers, & Theeuwes, 2005). One way to disentangle these effects is by using cues to provide advance knowledge on a trial-by-trial basis. Leonard and Egeth (2008) used a mixed design to compare word cues that either provided 100% valid information about an upcoming target color (“red” or “green”) or were noninformative (“either”) in a singleton search, while concurrently measuring impact of repeating versus switching target colors on successive trials. While similar search performance benefits from both advanced feature cuing and target repetition were observed, the results indicated these were separable and independent effects. However, along with other research (Müller & Krummenacher, 2006; Müller et al., 2003), these findings contrast with those of Theeuwes and Van der Burg (2011) who found evidence that advanced feature information affected early attentional selection only when target features repeated across trials (attributed to intertrial priming) or when the actual search feature (and not a symbolic word) was presented as a cue (attributed to automatic bottom-up priming from the cue itself; see also Theeuwes et al., 2006; Theeuwes & Van der Burg, 2007). The purpose of the present study was to explore the dynamics of how and when nonspatial information provided by endogenous cues impact oculomotor selection during visual search. In doing so, we sought to extend existing research by examining cue impact across the latency distribution of oculomotor responses, using a mixed design that allowed measurement of intertrial priming effects.

Because eye movements determine the quality of early visual information processing, they represent a form of behavior more implicit and sensitive than manual button-press responses, effectively reflecting a real-time measure of the overt allocation of visual attention. Recent research on oculomotor selection in visual search has highlighted the importance of examining when a response is made relative to stimulus onset. Early saccades following a display presentation are more likely to be made to the most physically salient stimuli regardless of task-relevance (Godijn & Theeuwes, 2002; Ludwig & Gilchrist, 2002; Mulckhuyse, van Zoest, & Theeuwes, 2008). As saccade latency increases, so, too, does the likelihood that the saccade is directed to the task-relevant item (Donk & van Zoest, 2008; van Zoest & Donk, 2005, 2008; van Zoest et al., 2004; see also Hickey, van Zoest, & Theeuwes, 2010, for complementary results with covert attentional shifts). Using this approach, van Zoest and Donk (2008) interestingly demonstrated a benefit of task instructions on the earliest 20% of saccadic responses in a search task requiring discrimination of targets from unique distractors based on color. While these data suggest a potentially early role for goal-directed guidance based on advanced nonspatial information, such conclusions are precluded by use of a blocked (rather than mixed) design which could not rule out a bottom-up intertrial priming account of the findings. By examining saccadic accuracy as a function of saccade latency, the present study will add a further layer of understanding to the dynamic nature of when and how cue information influences selection, providing greater scope to reconcile existing findings.

The second motivation of the present study was to investigate how individual differences in visual working memory (VWM) capacity influences overt selection performance. VWM is broadly considered to be a capacity-limited cognitive resource involved in the active “on-line” maintenance of information to perform current tasks (Cowan, 2001). Within the context of visual search, VWM has been implicated as a crucial mechanism that defines and maintains active representations of task-relevant items, creating feature templates necessary to select task-relevant targets and reject task-irrelevant distractors (e.g., Bundesen, Habekost, & Kyllingsbaek, 2005).

Stable differences in VWM capacity across healthy individuals are highly correlated with higher order
cognitive functioning (Cowan et al., 2005; Fukuda, Vogel, Mayr, & Awh, 2010), and a wealth of research has found significant differences between individuals with high versus low VWM capacity in a wide range of cognitive tasks where attentional control was necessary for successful performance (e.g., Bleckley, Durso, Crutchfield, Engle, & Khanna, 2003; Heitz & Engle, 2007; Poole & Kane, 2009; Sobel, Gerrie, Poole, & Kane, 2007; Vogel, McCollough, & Machizawa, 2005). Consequently, it has been posited that VWM is closely linked with attentional processes and that an individual's VWM capacity reflects the degree to which attentional control can be exerted in order to select and maintain task-relevant information in the presence of distraction. Individual differences in VWM capacity would thus be expected to predict differential performance in a cognitive task requiring attentional control. In the present experiment we used a color change-detection task to estimate VWM capacity (as in Luck & Vogel, 1997) and correlated performance in this task with the main oculomotor search task.

The primary experiment involved a modified visual search task where eye movements were recorded while participants searched for a specific orientation target. In the uncued half of the experiment, participants were not provided with any additional information regarding the secondary features of the display (i.e., basic replication of van Zoest & Donk, 2008, experiment 1). In the cued half of the experiment, participants were given specific information regarding a secondary feature of the upcoming display by means of a word cue. Thus, while the primary search task was alike in both experimental sessions, participants received more or less relevant information regarding the additional features in the display.

More specifically, the basic experiment instructed participants to select a particular line orientation in a visual search task by making an eye movement to its location. In addition to the target, a second uniquely oriented singleton was always present in the search display. Target and distractor lines were equally salient in terms of orientation-contrast relative to the non-targets. The target line or the distractor line could also be unique in color (creating a salient color singleton) or when no extra color was applied, could both be equally salient. In the uncued part of the experiment, participants were solely provided with the word “ready.” In the cued part of the experiment, the singleton identity (target-color singleton, distractor-color singleton, or no-color singleton) was validly cued prior to each trial. Importantly, these cues provided additional information allowing the use of the more salient dimension of color to assist selection in a goal-directed manner. Whereby identifying the target in advance as a color singleton effectively indicated oculomotor selection could be guided to the most salient feature (in concert with stimulus-driven processes); identifying the distractor as a color singleton indicated the need to guide selection away from the most salient feature (requiring the override of stimulus-driven processes). Given these cues could vary trial by trial, ongoing and active attentional control became necessary to derive benefit from them. In order to maximize impact, cues not only identified the status of the singleton (target vs. distractor), but also the dimension (color) and feature value (red) of the singleton, with 100% accuracy. Therefore cues were highly informative and useful for efficient selection of the target.

A mixed design was used by varying (rather than holding constant) the status of the color singleton (target-color singleton, distractor-color singleton, or no-color singleton) across trials within cued and uncued conditions. Consequently, the average likelihood of target status as a color singleton repeating versus changing on consecutive trials was equal across both cued and uncued conditions, ensuring that potential effects of intertrial priming were matched between cue conditions. Symbolic word cues were used to avoid bottom-up priming from presenting the feature itself as a cue. This design also allowed independent investigation into the dynamic contributions of passive intertrial priming, by comparing the time-course of performance on trials where target singleton status had repeated versus switched from previous trials. Taken together, it could be examined how the dual contributions of stimulus-driven intertrial priming and goal-directed use of cue information combine to guide selection.

It was predicted that when the target was a color singleton, the presence of a valid cue would result in superior task performance (i.e., response speed and/or accuracy). Again, the idea being that goal-directed guidance would further benefit selection of the salient color target. Stimulus-driven control accounts of oculomotor selection would suggest that initial selection is guided only by stimulus-driven processes and so would predict an additional accuracy benefit from the cue to be observed only for later saccadic responses (i.e., following initial attentional selection). However, goal-directed control accounts would indicate that initial selection can be guided by goal-directed processes, such that a cue accuracy benefit would be observed from the earliest saccadic responses (e.g., Wolfe, 1994, 2007). Regardless, once this influence was observed, it was expected to rapidly asymptote to a maximum level of accuracy performance over the remaining time-course of saccadic responses.

Regarding distractor as a color singleton, the research is mixed as to whether a cue informing participants of the to-be-ignored feature could be expected to result in a performance benefit (Arita, Carlisle, & Woodman, 2012; Carlisle & Woodman,
2011; Munneke, Van der Stigchel, & Theeuwes, 2008; Sawaki & Luck, 2011; Theeuwes & Burger, 1998; Woodman & Luck, 2007) or cost (Moher & Egeth, 2012; Soto, Heinke, Humphreys, & Blanco, 2005; Soto, Humphreys, & Heinke, 2006). A primary question underlying these discrepant predictions concerns the degree to which goal-directed processes can overcome an initial bias to attend to the to-be-ignored distractor features matching WM content. Examining accuracy performance as a function of saccade latency may provide valuable insights to this question. An immediate and consistent accuracy benefit from the cue over the latency distribution of saccadic responses would indicate an ability to suppress distractor activation without first requiring attentional selection, while an accuracy cost, particularly for early saccadic responses, would suggest attentional selection may be prerequisite.

Regarding the predictions concerning VWM capacity, Woodman, Luck, and Schall (2007) demonstrated that increasing VWM load disrupted visual search when implementing trial-by-trial cuing of feature representations using the target stimulus itself as a cue. An important role by VWM was similarly predicted for the present experiment when semantically cuing feature representations using symbolic word cues, particularly given the task effectively required participants to generate, maintain, and coordinate feature templates with attentional deployment on a trial-by-trial basis. To this end, it was expected that individual differences in VWM capacity would predict differences in the ability to make use of the cues to control oculomotor selection, such that individuals with a higher VWM capacity would benefit more from the cue than those with lower VWM capacity.

Method

Participants

Twenty-seven participants completed the experiment in exchange for payment. All gave their informed consent but were naïve to specific experimental hypotheses. Data from two participants were excluded from primary analyses due to high error rates (>30% for either experimental session; cf. error criteria below). Of the remaining 25 participants (mean age = 23.92 years), 18 were female and all were right-handed with normal or corrected-to-normal vision.

Apparatus

The experiment was programmed using Matlab (version 7.11.1, The MathWorks, Inc., Natick, MA), run on a Pentium III Dell Precision T1600 PC (Dell, Łódź, Poland) and displayed on a 19-inch ViewSonic G90FB CRT monitor (ViewSonic, Munich, Germany) at a 100 Hz refresh rate and 1024 × 768 resolution. Participants were seated approximately 57 cm from the monitor and eye movements were measured using the EyeLink II Desktop Mount (SR Research, Ltd., Mississauga, Canada).

Stimuli, procedure, and design

Oculomotor search task

Stimuli consisted of a 17 × 17 rectangular matrix of line elements (approximate length of 0.68° visual angle) presented on a black background, subtending 29.11° × 21.86°. Target and distractor line elements were angularly oriented 45° to either the left or right. On every trial a target and a distractor were presented at two of four equidistant locations at the vertices of an imaginary square (approximately 10.75° × 10.75°) surrounding fixation, embedded within the matrix of vertical white nontargets. Angular distance between both target and distractor elements from central fixation was always 90°.

Trial procedure is presented in Figure 1. Each trial began with a drift correction. A central fixation point was presented for 200 ms, then replaced by a word cue in 17-point Arial font for 1000 ms. A fixation point was shown again for 400 to 600 ms, followed by the matrix, presented for 1500 ms. Participants were instructed to make a speeded saccade to the tilted element defined as the target (e.g., right-tilted) while ignoring the distractor defined by the opposite-tilted line element (e.g., left-tilted). Three singleton conditions (target-color singleton, distractor-color singleton, or no-color singleton) were presented with equal probability. Color singleton elements were red, while all other elements were white. For the cued condition, the word cue (“target,” “distractor,” or “nessun”) validly indicated which of either the target or distractor would be red in the subsequent matrix. For the uncued condition the word “pronto” (“ready” in Italian) was presented. Feedback was provided by warning tones signaling anticipative (<80 ms) or late (>600 ms) saccades and by presenting average reaction times at the end of each block.

Participants completed two approximately 1-hr experimental sessions on different days. Each session consisted of one cuing condition (cued or uncued) made up of 24 practice trials followed by 456 analyzable trials separated into 12 blocks. Location of targets and distractors, and singleton condition were counterbalanced within participants and presented in a random order within an experimental session. Target (and complementary distractor) orientation (left vs. right)
and experimental session order were counterbalanced across participants.

**Visual working memory capacity task**

At the beginning of the second session, participants also completed a brief color change detection task of 192 trials (preceded by 24 practice trials) to provide a measure of VWM capacity. Based on the same design as Luck and Vogel (1997), participants were briefly presented an array of four, six, or eight colored squares (each 1.3° × 1.3°) on a gray background for 100 ms. After a 900-ms interval, a second array was presented that could be either identical to the initial array or differed in the color of one square, with equal probability. Participants made a key press to indicate whether the two arrays differed or were the same. Accuracy was stressed and the second display remained until a response was made. Square locations were randomized within a 19.6° × 15.6° region and separated from each other by at least 4.0° center-to-center. Squares could randomly be one of seven possible colors with no more than two squares sharing a color. The location and new color of the square on change trials was also randomized. Using the formula by Cowan (2001) a measure of working memory capacity, $K$, was derived for each of the three array sizes, where $K = \text{set size} \times (\text{hit rate} + \text{false alarm rate})$, and then averaged together to give a single estimate of VWM capacity.

**Results**

Saccade reaction time (RT) was measured as the time taken to initiate the first saccade greater than 3° following presentation of the matrix. Saccades were defined when eye movement velocity exceeded 30°/s or acceleration exceeded 8000°/s². The initial saccade was assigned to either the target or distractor if it landed within 4° of their respective positions. Trials were excluded if the first saccade was launched more than 3° from central fixation (2.50% of trials), did not land at either target or distractor locations (5.61%), was anticipative (<60 ms; 0.29%) or late (> 2.5 standard deviations later than a participant’s mean saccadic latency; 2.53%). Combined, these criteria led to the overall exclusion of 10.07% of trials from the 25 participants included in the primary analyses.
The ANOVA for correct saccade RTs showed a significant main effect of cue condition, $F(1, 24) = 12.56, MSE = 1138.89, p < 0.002, \eta^2 = 0.34$, indicating that the presence of a cue resulted in faster RTs overall ($M = 224$ ms vs. $243$ ms). A significant main effect of singleton condition, $F(2, 48) = 91.08, MSE = 145.83, p < 0.001, \eta^2 = 0.79$, was revealed by Bonferroni-corrected comparisons to reflect faster RTs for singleton targets ($M = 215$ ms), $SE = 2.37, p < 0.001$, and slower RTs for singleton distractors ($M = 247$ ms), $SE = 2.32, p < 0.02$, relative to when both elements were white ($M = 239$ ms). No significant interaction was found ($F < 0.9$).

**Time-course analyses**

To examine the impact of the cue on performance over time, saccadic accuracy was examined as a function of saccade latency. Participants’ distribution of saccadic responses (to both targets and distractors) was individually separated evenly into quintiles according to response latency. Mean proportion of correct saccades and mean saccadic RT were then calculated within each quintile per participant. See Figure 3 for mean proportion of correct saccades (across participants) as a function of saccade latency bins for each cue × singleton condition. A three-way repeated measures ANOVA was conducted on mean proportion of correct saccades, using within-participants factors of cue condition, singleton condition, and saccade RT bin. All main effects and two-way interactions were significant ($p < 0.02$). Most importantly for the present analyses, a significant three-way interaction was observed, $F(4,41, 105.89) = 3.23, MSE = 0.02, p < 0.02, \eta^2 = 0.12$, prompting three further two-way ANOVAs (cue condition × saccade RT bin) to be conducted separately for each singleton condition. For the target-color singleton condition, significant main effects of cue condition, $F(1, 24) = 136.81, MSE = 0.03, p < 0.001, \eta^2 = 0.85$, and saccade RT bin, $F(2.32, 55.57) = 18.74, MSE = 0.03, p < 0.001, \eta^2 = 0.44$, were qualified by an interaction, $F(2.38, 57.13) = 5.63, MSE = 0.03, p < 0.01, \eta^2 = 0.19$. Intriguingly, follow-up one-way ANOVAs showed significant main effects of saccade RT bin for both cued, $F(4, 96) = 6.43, MSE = 0.01, p < 0.002, \eta^2 = 0.21$, and uncued target singleton conditions, $F(2.05, 49.11) = 13.64, MSE = 0.06, p < 0.001, \eta^2 = 0.36$. These results indicate that proportion of correct saccades decreased as saccade latency increased when target-color singletons were present, and that this seeming deterioration of accuracy performance over time was reduced, but not eliminated, when following cues. For the no-color singleton condition, a significant main effect of saccade RT bin was observed, $F(4, 96) =$

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**Proportions and correct saccade reaction times**

Figure 2 presents the mean proportion of saccades correctly directed to the target (saccades to targets divided by total saccades to targets and distractors) and latency of correct saccades as a function of cue and singleton conditions. Two two-way repeated measures ANOVAs were conducted using cue condition (cued vs. uncued) and singleton condition (target-color vs. no-color vs. distractor-color) as within-participants factors. The ANOVA for proportion of correct saccades revealed significant main effects of cue, $F(1, 24) = 76.55, MSE = 0.01, p < 0.001, \eta^2 = 0.76$, and singleton condition, $F(1.30, 31.13) = 45.08, MSE = 0.03, p < 0.001, \eta^2 = 0.65$. These main effects were qualified by a significant interaction, $F(2, 48) = 50.01, MSE = 0.01, p < 0.001, \eta^2 = 0.68$, which planned paired-samples $t$ tests showed to be driven by an accuracy benefit in the cued (vs. uncued) trials when the target (accuracy difference of 0.2553), $t(24) = 11.65, SE = 0.22, p < 0.001, d = 3.01$, or distractor (0.0806), $t(24) = 3.64, SE = 0.22, p < 0.002, d = 0.51$, was a color singleton, but not in the no-color singleton condition when both elements were white ($t < 0.35$). These results demonstrate that the cue was utilized by participants and improved accuracy performance.

Figure 2. (a) Mean proportion of saccades correctly directed to the target, and (b) mean saccade RTs for correct responses (ms); presented for cued and uncued trials as a function singleton condition. Error bars reflect standard errors.
12.50, $MSE = 0.01$, $p < 0.001$, $\eta^2 = 0.34$, whereby accuracy performance increased as a function of saccade latency. There was no significant main effect of cue, nor a cue $\times$ saccadic RT interaction (remaining $F$ values $<$ 0.7). For the distractor-color singleton condition, significant main effects were observed of cue, $F(1, 24) = 13.48$, $MSE = 0.03$, $p < 0.002$, $\eta^2 = 0.36$, and saccade RT bin, $F(2.59, 62.04) = 73.35$, $MSE = 0.04$, $p < 0.001$, $\eta^2 = 0.75$, the latter reflecting increased performance accuracy with later saccades. No cue $\times$ saccadic RT interaction was observed ($F < 1.2$), indicating a consistent benefit of cue on performance accuracy across the distribution of saccadic responses when the distractor was the color singleton.

Planned contrasts using two paired-samples two-tailed $t$ tests showed increased performance accuracy for cued versus uncued trials in the earliest saccade RT bin, both when target-color ($M = 0.9478$ vs. $0.8370$), $t(24) = 4.28$, $SE = 0.03$, $p < 0.001$, $d = 1.24$, and distractor-color ($M = 0.2697$ vs. $0.2086$), $t(24) = 2.37$, $SE = 0.03$, $p < 0.03$, $d = 0.36$, singletons were present in the search display. These contrasts indicate that cues influenced oculomotor selection from the earliest 20% of saccade responses analyzed.

**Correlations with visual working memory capacity**

To explore the role that individual differences might play in the utilization of the cue to benefit performance, two-tailed correlational analyses were conducted on the relationship between participants’ individual VWM capacity estimates and the benefits conferred by the cue in terms of saccadic accuracy and RT for each of target-color and distractor-color singleton conditions. Estimates of VWM capacity ($K$) ranged from 1.63 to 4.38, with a mean of 3.10.

For suitable comparison, a simple logistic regression was conducted to transform accuracy proportions into log odds of a correct saccade for each participant. Figures 4a and 4b present these correlations. A positive correlation was found between VWM capacity scores and cue impact on saccade accuracy (cued minus uncued log odds) for singleton targets, $r(25) = 0.47$, $p <$
indicating that those participants with higher VWM capacity estimates tended to have greater improvements in saccadic accuracy from the cue when the target was a color singleton. A similar relationship was absent for distractor-color singletons ($p = 0.05$).

Positive correlations were found between VWM capacity and cue impact on saccade RTs (uncued minus cued mean RT) for both singleton targets, $r(25) = 0.48, p < 0.02$, and singleton distractors, $r(25) = 0.50, p < 0.02$, showing that participants with higher estimates of VWM capacity tended to receive greater RT benefits from the presence of the cue (see Figure 4c).

Comparing the size of these latter two correlation coefficients using a method based on Meng, Rosenthal, and Rubin (1992) did not reveal a significant difference ($z = 0.23, p > 0.05$). The no-color singleton condition was not submitted to further analyses due to the null results obtained in the time-course analyses.

**Intertrial priming analyses**

The extent to which the cue impact on selection speed and accuracy for target-color singletons reflected intertrial priming effects was examined by making comparisons between performances on trials where a target-color singleton had repeated versus switched from a distractor-color singleton in the previous trial. The mean proportion and latency of correct saccades as a function of each cue condition are presented in Figures 5a and 5b, respectively. A two-way repeated-measures ANOVA using cue condition and priming condition (repeat vs. switch) on correct saccade proportion yielded main effects of cue, $F(1, 24) = 132.81, MSE = 0.01, p < 0.001, \eta^2 = 0.85$, and priming, $F(1, 24) = 30.73, MSE = 0.04, p < 0.001, \eta^2 = 0.56$. Importantly, the interaction did not approach significance ($F < 1.0$), indicating that the relative contributions to accuracy from the cue (0.2559) and intertrial priming (0.0741) were additive. The same ANOVA on saccade RTs revealed a significant main effect of cue, $F(1, 24) = 16.19, MSE = 873.68, p < 0.001, \eta^2 = 0.40$, indicating faster saccades were made to target singletons when preceded by a valid cue ($M = 204$ ms vs. 227 ms). There was no significant main effect of priming, nor a cue $\times$ priming condition interaction (remaining $F$ values $< 1.9$). Together, these results indicate that both bottom-up intertrial priming and goal-directed cuing
effects significantly contribute to visual search performance (at least in terms of accuracy), but do so in an additive, not interactive, manner.

To explore the time-course of intertrial priming effects, a three-way repeated-measures ANOVA was conducted on proportion of accurate saccades to target-color singletons (Figure 5c). Within-participants factors included cue condition, priming condition, and saccade RT bin. The three levels of the saccade RT bin factor consisted of separating participants' saccadic response distribution for each cue · priming condition into tertiles according to response latency. A tertile, rather than quintile, split was necessary to maintain sufficient statistical power (M = 15.22 trials per bin). Main effects of cue, priming condition, and RT bin, as well as a cue · RT bin interaction were all significant (ps < 0.01). A priming · RT bin interaction was also significant, F(2, 48) = 3.70, MSE = 0.01, p < 0.05, η² = 0.13, suggesting that the effect of priming increased as saccadic response latency increased. More important was the lack of a significant three-way interaction between priming condition, cue and RT bin (remaining F values < 1.1). These findings demonstrate that even over the time-course of saccadic responding, intertrial priming effects did not interact with cue effects, and so could not account for the observed dynamic effects from the cue.

**Discussion**

Several important findings emerged from the results. A cue providing advanced knowledge about the color-singleton status in a search display facilitated speed (across all conditions) and accuracy (for target and distractor-color singletons) of oculomotor selection. The cue influenced dynamic oculomotor selection in three specific ways: (1) it increased accuracy performance from the earliest 20% of saccadic responses; (2) this accuracy benefit increased with later saccadic responses to target-color singletons; (3) this increasing benefit was sufficient to only reduce, and not eliminate, an overall decrease in accuracy performance as a function of response latency towards target-color singletons. Overall cue impact on performance was correlated with individual VWM capacity scores, such that higher VWM capacity scores were associated with
increased cue benefits in terms of accuracy (for target-color singletons) and response speed (for target and distractor singletons). Importantly, while intertrial priming effects on accuracy were observed when target singleton status was repeated, these effects were minimal and did not interact with the overall or dynamic effects from the cue.

In line with previous findings (e.g., Müller et al., 2003; Wolfe et al., 2004), cuing nonspatial information about upcoming properties of a search display was observed to enhance visual search performance. These endogenous cues provided an additional selection benefit by cuing the presence of a target-color singleton, indicating that goal-directed processes guided selection over and above a stimulus-driven bias resulting from target salience. That cuing the upcoming presence of a to-be-ignored salient distractor-color singleton also benefited target selection similarly indicated a role for goal-directed processes in improving selection of the less-salient target when competing with a stimulus-driven bias towards selection of the salient distractor. The key result was observing that cues influenced such selection from the earliest saccadic responses ($M = 167$ ms, for earliest 20% of analyzed saccades). This finding demonstrates that strategic use of cue information to select and reject salient singletons can develop very early following display presentation, suggesting an immediate or early role for goal-directed guidance in early oculomotor selection. While this finding contrasts with previous research claiming that rapid saccades are purely stimulus-driven (Godijn & Theeuwes, 2002; Ludwig & Gilchrist, 2002; Mulckhuyse et al., 2008), it is consistent with recent observations that VWM content can modulate speed and accuracy of rapid saccades (< 200 ms) in the absence of competition (Hollingworth, Matsukura, & Luck, 2013). Our findings align with theories that implicate a role for goal-directed pre-attentive guidance on the basis of nonspatial information, that is, where certain features or dimensions can be actively prioritized in advance, which can then be voluntarily used to pre-attentively guide selection to features across the visual field (Bundesen, 1998; Duncan & Humphreys, 1989; Folk et al., 1992; Müller et al., 2003; Serences & Boynton, 2007; Treisman & Sato, 1990; Wolfe, 1994, 2007).

Our findings rule out intertrial priming as an alternative explanation and so build on existing research observing early goal-directed impacts of nonspatial information (e.g., Treisman, 1988; van Zoest & Donk, 2008; Wolfe et al., 2003; Zhang & Luck, 2009). With respect to priming, the present results favor an additive interpretation, whereby goal-directed and passive priming processes appear to operate independently to influence initial oculomotor selection. Our results are consistent with those of Leonard and Egeth (2008) who similarly observed with singleton targets, which were already the most salient element in the display, that providing advanced knowledge of target features resulted in an additional attentional selection benefit separable from intertrial priming. Here we extend their findings to oculomotor selection, using response measures and analyses that provide a more sensitive and dynamic picture than what could be derived from mean manual-motor RTs. In this regard, our results showed that intertrial priming effects increased as a function of response latency, suggesting that such priming effects, if anything, might be less automatic and bottom-up than previously argued (e.g., Theeuwes, 2013) and instead may be more strategic (e.g., Wolfe et al., 2003). It could be that the target representation takes time to develop following its presentation, so that little representation would have developed at the earliest saccades where salience information dominates, whereas greater modulation of target-relevant information by priming occurs with later saccades, once a sufficient target representation has built up. More research would, however, be required to further substantiate this claim, particularly in light of recent research that suggests incidental trial factors may result in an under estimation of distractor interference (thereby artificially reducing priming effects) in the fastest saccade bins (Leber, Lechak, & Tower-Richardi, 2013).

The present results are inconsistent with those of Theeuwes and Van der Burg (2011), who did not observe an effect of cuing feature information on visual selection separable from priming. Several methodological differences may account for these discrepant results. The current paradigm employed a cue that provided additional information about upcoming target and distractor features, whereas Theeuwes and Van der Burg used cues that defined the target singleton itself, making it difficult to ascertain in their study whether cuing nonspatial information benefits selection relative to a control baseline where no additional information is provided. Other differences included our focus on overt (vs. covert) attentional selection and use of a simple saccadic localization task rather than a compound manual discrimination task where target-defining features (color) were dissociated from those defining the discrimination response (orientation). These differences mean that, while we can comment on how the cue influenced overt attentional selection, it is more difficult to convincingly distinguish between accounts regarding whether the cue enhanced perceptual sensitivity (i.e., by enhancing perception of red elements a priori) or biased oculomotor responding (i.e., by reducing uncertainty about whether to saccade towards the salient red singleton element) in the current task. While beyond the scope of our study, replicating the present modulatory effects from cuing when
measuring the N2pc ERP component preceding oculomotor responses or when measuring initial saccadic responses in a compound search task would provide evidence in support of a pre-attentive locus of cue influence.

Advanced knowledge about the saliency and features of to-be-ignored distractors helped observers guide selection away from the distractor and toward the target. These results are consistent with the results of work by Arita et al. (2012), who similarly found a performance benefit suggesting observers could use feature precues (they used the physical feature itself) to direct attention away from nontarget items during visual search. However, their task involved a more complex manual-motor discrimination task producing much longer response times (cue benefits were only observed with mean RTs > 900 ms), which cannot rule out initial selection of the to-be-ignored feature prior to its rejection/suppression. A performance benefit was observed in the present study from the earliest saccadic responses (< 200 ms), providing more convincing evidence that an initial bias toward attending to to-be-ignored features matching WM representations could be overridden without their first being selected. Our results might be explained by the signal suppression hypothesis as proposed by Sawaki and Luck (2010, 2011), which posits that attentional selection is the competitive outcome between an “attend-to-me” prioritization signal, which may be automatically generated by a to-be-ignored object’s stimulus-driven saliency and/or top-down matching with WM content, and a goal-directed control signal aiming to suppress such activity. Cuing to-be-ignored features of the distractor in the current paradigm would have then served to boost the top-down control signal thereby increasing the likelihood that saccades were directed away from the distractor.

The present experiment effectively replicated previous observations that saccades to the most salient element in a search display, whether target or distractor, became less likely as latency increased (Donk & van Zoest, 2008; van Zoest & Donk, 2008). Why a lower proportion of later saccades should be made to a target when it is the most salient element in a display is an intriguing question not easily explained by either a stimulus-driven or goal-directed process account. One explanation is that the drop in selection accuracy is the consequence of a rapid passive decay of early stimulus-driven activity (Cheal & Lyon, 1991; Donk & van Zoest, 2008; Nakayama & Mackeben, 1989; Nothdurft, 2002; Yantis & Jonides, 1990), such that the high target saliency is unable to influence later selection. An alternative explanation is that observers actively suppress salience activity (i.e., from color singletons) to be more in line with task instructions (i.e., attend to orientation), such that only saccades made prior to applied suppression are influenced by saliency information (Godijn & Theeuwes, 2002, 2004; McSorley, Haggard, & Walker, 2006; Theeuwes, Kramer, Hahn, & Irwin, 1998). Our results support the former explanation by demonstrating that even when observers had prior knowledge that the target would be a color singleton, selection accuracy performance still declined (albeit less so) as a function of saccade latency. That such a transient selection benefit observed when target saliency was incidental (i.e., one-third of trials) was only attenuated, and not eliminated, when target saliency was known in advance, indicates that such saliency information was less available to be used in a goal-driven manner to enhance later selection. The transient nature of saliency activity then appears to have a role in the observed performance decline of selecting salient targets over time.

Individual variation on the size of the cue impact on performance was predicted by individual VWM capacity scores. Participants with higher VWM capacity scores tended to receive a greater RT benefit from the cue for both target and distractor singletons, and a greater accuracy benefit for target singletons. These results indicate that the ability to strategically use cue information to improve efficiency and effectiveness of oculomotor selection appears to be related to VWM capacity. VWM capacity has been considered to reflect ability to control which information accesses VWM (e.g., Vogel et al., 2005), indicating that individuals with higher VWM capacity should be better able to use attentional control to select task-relevant information while filtering out task-irrelevant information. Because attentional control was required to derive a selection benefit from the trial-by-trial cuing, the present results support the view that the greater cue benefit enjoyed by individuals with higher VWM capacity was a result of superior attentional control. The present findings add to a growing literature finding that individual differences in VWM capacity measures can predict individual differences in performance on tasks requiring attentional control (Luck & Vogel, 2013).

However, while we found a reliable correlation with target selection and VWM capacity, we did not obtain a similar relationship with VWM capacity and distractor inhibition. Previous research has implicated orienting (specifically, disengagement from to-be-ignored elements; Fukuda & Vogel, 2011) or executive control (e.g., Hiebel & Zimmer, 2013; Sobel et al., 2007) as the attentional mechanisms underlying VWM capacity. However, whereas with higher VWM capacity scores we observed both a greater speed and accuracy cue benefit for salient target singletons, orienting or executive control accounts would predict the greatest differences when cuing the to-be-ignored salient distractor, where we observed only a greater benefit for speed. The increased speed benefit observed from all
cues as a function of VWM capacity may instead suggest that alerting mechanisms of attention were differentially affected in the present task, whereby cues more greatly increased alertness for higher VWM capacity individuals. The present findings, however, cannot realistically specify which mechanisms of attentional control were indexed by VWM capacity in the current task and distinguishing between hypotheses regarding the roles of alerting, orienting, and executive attentional control mechanisms in VWM capacity might be better achieved in future research by utilizing the Attentional Network Test (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002).

Taken together, the current research demonstrates that strategic use of cue information to select and reject salient singletons can develop very early following display presentation. The efficiency and effectiveness of such strategic use is related to an individual’s visual working memory capacity and develops independently of bottom-up priming processes. This research indicates that stimulus-driven and goal-directed processes are not simply additive in oculomotor selection, but instead exhibit a distinct and dynamic profile of interaction.

Keywords: eye movements, visual search, oculomotor selection, individual differences, visual working memory capacity

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References


