Tracking target and distractor processing in visual search: Evidence from human electrophysiology

by

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Abstract

The issue of whether salient distractors capture attention has been contentious for over 20 years. According to the salience-driven selection theory, the most salient location in the display is detected preattentively, after which attention is deployed automatically to that location. By other accounts, attentional deployment to the location of an item is contingent upon the task-relevance of that item. In the present work, six experiments employed the event-related potential (ERP) technique to examine the salience-driven selection and other theories of visual search. The experiments adopted additional singleton search, pop-out detection, and attentional-window paradigms. The ERP evidence obtained from the additional-singleton paradigm indicated that although the location of a salient item – whether a target or a distractor – was registered relatively early, the salient distractor did not capture attention consistently. Moreover, when the features of the salient distractor were held constant, observers were occasionally able to suppress the location of the distractor, thereby improving the efficiency of the search. The ERP evidence obtained from a Go/No-Go pop-out detection task indicated that attention was deployed to the location of a pop-out item only when a decision to search was made and, thus, that item was relevant to the observer’s goals. The ERP evidence obtained from the attentional-window paradigm indicated that goal-driven control over stimulus salience could extend to the items located within the observer’s attentional window. The present results suggest that while the locations of a limited number of salient items in the display can be registered on an early salience map, there is some goal-driven control over attentional deployment to the location of salient items or suppression of such locations. Factors that are potentially important in this dynamic control include the task-relevance of the search display, the predictability of distractor features, and inter-trial changes in target and distractor features and their task-relevance.

Keywords: visual attention; visual search; attention capture; human electrophysiology; event-related potentials
Dedication

To my parents
for their love, sacrifices, and encouragement
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# Table of Contents

Approval .............................................................................................................................ii
Partial Copyright Licence .................................................................................................. iii
Ethics Statement ................................................................................................................ iv
Abstract ............................................................................................................................. v
Dedication .......................................................................................................................... vi
Acknowledgements .......................................................................................................... vii
Table of Contents ............................................................................................................ viii
List of Tables ..................................................................................................................... xi
List of Figures .................................................................................................................... xii
List of Acronyms .............................................................................................................. xiv

## Chapter 1. General Introduction ................................................................. 1

1.1. Salience-driven selection ......................................................................................... 2
1.2. Alternative theoretical accounts of attentional control .............................................. 4
  1.2.1. Contingent capture ....................................................................................... 4
  1.2.2. Guided Search .............................................................................................. 6
  1.2.3. Integrated priority .......................................................................................... 7
       Selection history ........................................................................................... 8
       Reward history ............................................................................................. 9
       Integrative framework ............................................................................... 10
1.3. ERP indices of selection in visual search ..................................................................... 11
  1.3.1. The N2pc .................................................................................................... 11
  1.3.2. Beyond the N2pc ........................................................................................ 13

## Chapter 2. Salience-driven capture by fixed-feature and variable-feature distractors .......... 17

2.1. Introduction ............................................................................................................ 17
2.2. Experiment 1 .......................................................................................................... 20
  2.2.1. Methods ...................................................................................................... 21
   Participants ................................................................................................. 21
   Apparatus ................................................................................................... 21
   Stimuli and Procedure ................................................................................ 22
   Electrophysiological Recording .................................................................. 23
   Data analyses ............................................................................................. 24
   Behaviour ................................................................................................... 24
   Electrophysiology ................................................................................. 24
  2.2.2. Results ........................................................................................................ 26
   Behaviour ................................................................................................... 26
   N2pc and P0 ............................................................................................. 28
   Ppc ....................................................................................................... 33
   PT ............................................................................................ 34
   SPCN .................................................................................................... 35
  2.2.3. Discussion .................................................................................................. 36
2.3. Experiment 2 .......................................................................................................... 38
  2.3.1. Methods ...................................................................................................... 39
Chapter 4. The role of attentional window in salience-driven selection ........ 87
4.1. Introduction ............................................................................................................ 87
4.2. Experiment 6 .......................................................................................................... 90
  4.2.1. Methods ...................................................................................................... 90
    Participants ................................................................................................. 90
    Apparatus ................................................................................................... 90
    Stimuli and Procedure ............................................................................... 90
    Electrophysiological Recording and Data Analyses ................................... 92
  4.2.2. Results and Discussion .............................................................................. 93
    Behaviour ................................................................................................... 93
    Electrophysiology ....................................................................................... 93
      N2pc ..................................................................................................... 93
      Ppc ....................................................................................................... 94
      SPCN .................................................................................................... 95

Chapter 5. General Discussion ............................................................................ 96

References ................................................................................................................... 104
List of Tables

Table 1. Grand Averages Across Participants Of Median Response Times (In Milliseconds) For All Distractor-Present And Distractor-Absent Trials And For The Display Configurations Of Interest In Experiments 1 And 2 .................................................................................................................... 28

Table 2. Grand Averages Across Participants Of Median Response Times (In Milliseconds) On Fast-Response And Slow-Response Trials For All Distractor-Present And Distractor-Absent Displays And For The Search-Display Configurations Of Interest In Experiment 1 .......................... 29

Table 3. Grand Averages Across Participants Of Median Response Times (In Milliseconds) For All Distractor-Present And Distractor-Absent Trials And For The Display Configurations Of Interest In Experiment 3 ................. 53

Table 4. Grand Averages Across Participants Of Median Response Times (In Milliseconds) On Fast-Response And Slow-Response Trials For All Distractor-Present And Distractor-Absent Displays And For The Search-Display Configurations Of Interest In Experiment 3 .......................... 54
List of Figures

Figure 1. Hypothetical sequence of processes in additional-singleton search is shown, based on the salience-driven selection account. Here, selection is considered to take place when information at one location is transferred from the preattentive stage to the attentive stage for further processing (cf. Theeuwes, 2010). Four lateralized ERP components have been associated with specific processing stages (see text for details). ................................................................. 14

Figure 2. All-trials ERPs recorded at PO7/8 in Experiment 1. Panels a–c show the ERPs elicited by displays containing only one lateral singleton, whereas panels d and e show the ERPs elicited by displays containing two lateral singletons, either on opposite sides (d) or the same side (e). The target singleton was a green circle among green diamonds. The distractor singleton (dashed diamond) was a red diamond. Negative voltages are plotted up, by convention .................. 31

Figure 3. ERPs recorded at electrodes PO7 and PO8 in Experiment 1, averaged separately for fast-response and slow-response trials .............. 32

Figure 4. ERLs from Experiment 1. Upward and downward deflections reflect negative and positive voltages contralateral to the eliciting stimulus, respectively. (a) All-trials ERLs from the five display configurations of interest. (b) ERLs for isolation displays (containing one lateral singleton and one midline singleton), separately for fast-response and slow-response trials. ................................................................. 33

Figure 5. All-trials ERPs recorded at electrodes PO7/8 in Experiment 2. Panels a–c show the ERPs elicited by displays containing only one lateral singleton, whereas panels d and e show the ERPs elicited by displays containing two lateral singletons, either on opposite sides (d) or the same side (e). ................................................................. 42

Figure 6. All-trials ERLs from the five display configurations of interest in Experiment 2 ............................................................................. 43

Figure 7. All-trials ERPs recorded at electrodes PO7/8 in Experiment 3. Panels a–c show the ERPs elicited by displays containing only one lateral singleton, whereas Panels d and e show the ERPs elicited by displays containing two lateral singletons, either on the same side (d) or opposite sides (e). ............................................................................. 52

Figure 8. ERPs recorded at electrodes PO7 and PO8 in Experiment 3, averaged separately for fast-response and slow-response trials .......... 56
Figure 9. ERLs from Experiment 3. Upward and downward deflections reflect negative and positive voltages contralateral to the eliciting stimulus, respectively. (a) All-trials ERLs from the five display configurations of interest. (b) ERLs for isolation displays (containing one lateral singleton and one midline singleton), separately for fast-response and slow-response trials. .......................... 57

Figure 10. ERPs recorded at electrodes PO7/8 in Experiment 4. The top and bottom panels show the ERPs elicited on Go trials and No-Go trials, respectively. ................................................................. 73

Figure 11. Contralateral-ipsilateral difference waveforms recorded at electrodes PO7/8 for Go-Repeat and Go-Change trials in Experiment 4. The arrows indicate the 70% fractional peak latency of the N2pc. .......................... 75

Figure 12. Contralateral-ipsilateral difference waveforms recorded at electrodes PO7/8 for No-Go-Repeat and No-Go-Change trials in Experiment 4. The ERLs in the N2pc time range were not significantly different from zero. ................................................................. 76

Figure 13. ERPs recorded at electrodes FPz, Cz, and Oz in Experiment 4. The Go and No-Go ERPs began to diverge in the pre-N2pc time range, eliciting the P2a over the anterior scalp (FPz) and the N2b over the medial occipital scalp (Oz). The No-Go P3 component was prominent over the central scalp (Cz). ................................................................. 77

Figure 14. ERPs recorded at electrodes PO7/8 for all trials in Experiment 5. .............. 82

Figure 15. Contralateral-ipsilateral difference waveforms recorded at electrodes PO7/8 for Go trials in Experiment 4 and all trials in Experiment 5. The arrows indicate the 70% fractional peak latency of the N2pc. .................. 82

Figure 16. Contralateral-ipsilateral difference waveforms recorded at electrodes PO7/8 for Colour-Repeat and Colour-Change trials in Experiment 5. The arrows indicate the 70% fractional peak latency of the N2pc. ............... 83

Figure 17. ERPs recorded at electrodes PO7/8) in Experiment 6. The top and bottom panels illustrate the ERPs obtained in the Target-Disk and Target-Bar conditions, respectively. The top display illustrates a long bar inside a large disk, whereas the bottom display illustrates a short bar inside a small disk. .................................................................................. 91

Figure 18. Contralateral-ipsilateral difference waveforms recorded at electrodes PO7/8 for Target-Disk and Target-Bar conditions in Experiment 6. ............... 94

Figure 19. Hypothetical sequence of processes in additional-singleton search, based on the salient-signal suppression hypothesis proposed here. Six lateralized ERP components are associated with specific processing stages (see text for details). ................................................................. 103
## List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
</tr>
<tr>
<td>ACC</td>
<td>Anterior cingulate cortex</td>
</tr>
<tr>
<td>EEG</td>
<td>Electroencephalogram</td>
</tr>
<tr>
<td>ERL</td>
<td>Event-related lateralization</td>
</tr>
<tr>
<td>ERP</td>
<td>Event-related potential</td>
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<td>ERPSS</td>
<td>Event-related Potential Software System</td>
</tr>
<tr>
<td>FIT</td>
<td>Feature Integration Theory</td>
</tr>
<tr>
<td>HEOG</td>
<td>Horizontal electro-oculogram</td>
</tr>
<tr>
<td>IPS</td>
<td>Intraparietal sulcus</td>
</tr>
<tr>
<td>MFG</td>
<td>Middle frontal gyrus</td>
</tr>
<tr>
<td>N2b</td>
<td>The second negativity, b subcomponent</td>
</tr>
<tr>
<td>N2pb</td>
<td>N2, posterior bilateral</td>
</tr>
<tr>
<td>N2pc</td>
<td>N2, posterior contralateral</td>
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<tr>
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<td>Target negativity</td>
</tr>
<tr>
<td>P1</td>
<td>The first positivity</td>
</tr>
<tr>
<td>P2a</td>
<td>The second positivity, a subcomponent</td>
</tr>
<tr>
<td>P3</td>
<td>The third positivity</td>
</tr>
<tr>
<td>PD</td>
<td>Distractor positivity</td>
</tr>
<tr>
<td>Ppc</td>
<td>Positivity, posterior contralateral</td>
</tr>
<tr>
<td>PT</td>
<td>Target positivity</td>
</tr>
<tr>
<td>Ptc</td>
<td>Positivity, temporal contralateral</td>
</tr>
<tr>
<td>RANOVA</td>
<td>Repeated-measures analysis of variance</td>
</tr>
<tr>
<td>RGB</td>
<td>Red, Green, Blue</td>
</tr>
<tr>
<td>RT</td>
<td>Reaction time</td>
</tr>
<tr>
<td>SPCN</td>
<td>Sustained posterior contralateral negativity</td>
</tr>
<tr>
<td>Tl/DA</td>
<td>Lateral target, no distractor</td>
</tr>
<tr>
<td>Tl/Dc</td>
<td>Lateral target, contralateral distractor</td>
</tr>
<tr>
<td>Tl/Dl</td>
<td>Lateral target, ipsilateral distractor</td>
</tr>
<tr>
<td>Tl/Dm</td>
<td>Lateral target, midline distractor</td>
</tr>
<tr>
<td>Tm/Dl</td>
<td>Midline target, lateral distractor</td>
</tr>
<tr>
<td>V1</td>
<td>Primary visual cortex</td>
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<tr>
<td>VSTM</td>
<td>Visual short-term memory</td>
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</tbody>
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Chapter 1.

General Introduction

The number of objects falling within our field of view typically exceeds our brain’s capacity to perceive and remember environmental events. Observers can deal with this potentially overwhelming surplus of information by attending to a specific region of the visual field in order to selectively process stimuli appearing there (Desimone & Duncan, 1995; LaBerge, 1995). At any given moment, two complementary control processes interact to determine which location is to be attended next: (1) goal-driven control processes that bias attentional selection toward objects of interest; (2) stimulus-driven control processes that bias attentional selection toward physically salient items. Two main perspectives have emerged regarding the role of each process in attentional selection. According to one perspective, attention is deployed initially to the most salient item in the visual field, regardless of its relevance to the task at hand (Theeuwes, 1991, 1992, 1994a,b, 2010). According to the other perspective, such salience-driven capture of attention can be prevented when an observer knows in advance what to look for, so that attention can be deployed directly to a relevant, but less salient, stimulus (Anderson & Folk, 2010; Bacon & Egeth, 1994; Folk & Remington, 1998, 2006; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994; Müller, Reimann, & Krummenacher, 2003; Wolfe, 1994; Wolfe, Butcher, Lee, & Hyle, 2003).

Evidence for stimulus-driven control has been obtained from the additional-singleton paradigm, in which observers search covertly for a target singleton while trying to ignore an irrelevant distractor singleton in the same display (Theeuwes, 1991, 1992, 1994a). The target and distractor “pop out” from the rest of the items in the display because they each possess a unique feature. The distractor singleton is typically chosen to pop out even more than the target singleton, so that the distractor’s bottom-up salience and the observer’s current goal are in opposition and will thus compete for attentional selection. In this case, the presence of the irrelevant-but-salient distractor
delays search for the less-salient target. For example, Theeuwes (1991) reported that a salient colour-singleton distractor delayed search for a less-salient shape-singleton target by 120–150 ms when the features of the target and the distractor swapped randomly from trial to trial. Under these mixed-feature conditions, participants know that the target will be the unique shape, but they do not know what shape or colour it will be on any given trial. The delay is reduced considerably, although still significant, when the features of the stimuli are fixed across trials. For example, Theeuwes (1992) reported that a salient colour-singleton distractor delayed search for a less-salient shape-singleton target by 20–25 ms in a fixed-feature variant of the additional-singleton paradigm.

1.1. Salience-driven selection

The results obtained from the additional-singleton paradigm gave rise to the salience-driven selection theory, according to which the initial visual selection is determined entirely by bottom-up activations associated with stimulus salience (for a recent review, see Theeuwes, 2010). In the context of this theory, selection is defined as the transfer of information from an early “preattentive” stage of processing to a subsequent “attentive” stage of processing. It is assumed that, during the preattentive stage, basic visual features like orientation and colour are processed in parallel across the entire visual field and that stimulus salience is computed within the currently attended region of the field (i.e., the attentional window; Belopolsky & Theeuwes, 2010; Belopolsky, Zwaan, Theeuwes, & Kramer, 2007).

After the initial preattentive analyses, sensory information stemming from the location with the highest computed salience is automatically transferred to the attentive stage for further processing. This spatial selection is assumed to be impervious to the observer’s goals and intentions. By this account, attention is deployed automatically to the location of the most salient item – that is, attention is said to be captured. Proponents of the salience-driven selection theory suggest that capture can only be prevented by narrowing the focus of attention so that the most salient item falls outside the attentional window (and thus the salience of that item is not computed preattentively).
From this theoretical perspective, the sequence of visual processing events on an individual trial of a typical additional-singleton experiment is said to be as follows (Theeuwes, 2010): The location of the most salient item (i.e., the one with the highest local contrast) is determined preattentively, and then attention is deployed to that spatial location in order to identify the item appearing there. If the item at the attended location is identified as the target, the observer processes the orientation of the line inside the shape and then makes a response accordingly. If the item is identified as the distractor, attention is disengaged from that location so that it can be deployed to the location of the next most salient item (i.e., the target in typical additional-singleton experiments).

This sequence of visual processing events has been hypothesized to take place in fixed-feature as well as mixed-feature search tasks. Why then does the presence of a salient distractor cause much greater interference in mixed-feature search tasks than in fixed-feature tasks? According to Theeuwes (2010), the magnitude of the interference effect is determined by the speed with which attention can be disengaged from the distractor location after capture has taken place. This in turn depends on the time required to identify and discard the distractor. The time required to determine whether the item that initially captured attention is the target or distractor is assumed to depend on factors such as stimulus variability. In fixed-feature search, the item can be identified rapidly because there is no uncertainty stemming from stimulus variability. Thus, in this case, attention can be disengaged from the distractor location quickly, resulting in little RT interference.

In mixed-feature search, however, it takes considerably longer to identify the item as target or distractor because the features change across trials and the target and distractor can actually swap – that is, a stimulus such as a green diamond can change from being the target (appearing among green circles) to being the distractor (appearing among red diamonds) across successive trials. Accordingly, it takes more time to disengage attention from the distractor location in mixed-feature search tasks, resulting in greater RT interference. It is also possible that a process akin to negative priming (Tipper, 1985, 2001) underlies greater RT interference in mixed-feature search tasks. Namely, since target and distractor can reverse across successive trials, the observer might inhibit (or ignore) an item, e.g., a red diamond among green diamonds, on the present trial and then have to process that item as a target, e.g., a red diamond among
red circles, on the next trial. In sum, when there is more stimulus variability, distractors do not cause more capture, but it does take additional time to decide whether the item selected is a target or a distractor.

1.2. Alternative theoretical accounts of attentional control

1.2.1. Contingent capture

Evidence for goal-driven control of attention has been obtained from a modified spatial cueing paradigm (Folk et al., 1992, 1994; Folk & Remington, 1998, 1999, 2006; Gibson & Kelsey, 1998). In this paradigm, the observers are first presented with a ‘cueing’ display that contains a distractor singleton at one of four locations. The cueing display is followed by a target-singleton display that contains the target at one of the same four locations. Since the location of the distractor is entirely unrelated to the location of the target, observers have no incentive to voluntarily deploy their attention to the distractor location. Thus, any cueing effect is attributed to the involuntary capture of attention to the distractor location.

In one of the first studies employing the spatial cueing paradigm (Folk et al., 1992), two conditions were presented: an abrupt-onset target condition, in which a character appeared suddenly at one of the four locations, and a colour target condition, in which one red character appeared in one location while three white characters appeared in other locations. Each target condition was assumed to induce a corresponding attentional set. For example, the colour target condition would induce an attentional set for colour. The preceding distractor display could also contain either an abrupt-onset distractor or a colour distractor. Folk et al. found that the distractor singleton appeared to capture attention only when the defining features of target and distractor singletons matched (e.g., both were colour singletons). Thus, for example, a distractor colour singleton did not appear to capture attention when participants searched for a subsequent abrupt-onset target (Folk et al., 1992; but see Theeuwes, 2010, for an alternative explanation).

Folk and Remington (1998) obtained similar results when the target and distractor singletons were both colour singletons, but each could be either red or green.
They found that the distractor singleton captured attention only when it had the same colour as the target singleton. These results gave rise to the contingent-capture perspective (Folk & Remington, 1998, 1999, 2006), according to which, the defining feature of the target induces an attentional set that is specific to that feature. The distractor singleton presented in the distractor display is said to be detected preattentively, but it captures attention only when its defining feature matches the defining feature of the target, and, therefore, is consistent with the observer’s attentional set.

If the observer’s attentional set overrides capture of attention, why does a distractor singleton in the additional-singleton paradigm – that does not match the observer’s attentional set – still produce an interference effect? Two main explanations have been suggested from the perspective of goal-driven control of attention to account for this finding. The first explanation, offered by Bacon and Egeth (1994), is based on the notion of “search mode”. According to this account, when the target in the additional-singleton paradigm is a singleton defined in a given dimension such as shape (i.e., a diamond among circles or vice versa), observers are encouraged to adopt a “singleton search mode”. In this mode, observers are set to search for all singletons regardless of the dimension in which they are defined. The finding that a distractor singleton seems to capture attention is thus considered to be consistent with the contingent capture perspective. This is because such a singleton would match the observer’s attentional set of an observer in a singleton search mode. In contrast, when observers are asked to search for a target defined by a specific feature, they are said to adopt a “feature search mode”, in which distractor singletons produce no interference effect (Bacon & Egeth, 1994; but see Theeuwes, 2004, for an alternative explanation).

The second explanation for the distractor-interference effect in the additional-singleton paradigm, offered by Kahneman, Treisman, and Burkell (1983), is based on the notion of “nonspatial filtering costs”. According to this account, the distractor-interference account does not reflect an initial attention capture by the distractor singleton. It instead reflects a delay in the deployment of attention to the target as the visual system determines to which singleton attention should be deployed. Evidence in support of this account was obtained in the context of the spatial cueing paradigm. Specifically, a distractor that did not share the target’s defining feature – and did not
show any evidence of attention capture – still produced a behavioural cost relative to the trials with no distractor (Folk & Remington, 1998; but see Theeuwes, 1996, for an alternative explanation, and Folk & Remington, 2006 for rebuttal).

1.2.2. **Guided Search**

Guided Search refers to a model of human visual search that attempts to account for reaction time and accuracy data in a range of visual search tasks (Wolfe, 1994, 2007; Wolfe, Cave, & Franzel, 1989; Wolfe & Gancarz, 1996). According to this account, when observers search for a target, they are more likely to attend to items of the correct color, shape or size, i.e., features that match the target’s features. These basic visual features are said to “guide” the deployment of attention (for a review, see Wolfe & Horowitz, 2004).

Guided Search was originally inspired by the influential Feature Integration Theory (FIT; Treisman, 1988; Treisman & Gelade, 1980), which proposed a two-stage mechanism for visual search: (i) an initial, “preattentive” feature-processing stage, in which single basic features such as color, luminance, and motion are processed in parallel across the whole search display, giving rise to feature maps; (ii) an “attentive”, serial binding stage, during which the basic features at the locus of attention are bound together (cf. Broadbent, 1958; Hoffman, 1979; Neisser, 1967).

The two-stage architecture is incorporated into Guided Search with the added principle that the information obtained in the preattentive stage could guide the subsequent deployment of attention. An example can be seen when an observer is searching for a target defined by the conjunction of two features such as a small red circle among big red and small green circles. Under these circumstances, the search task is presumed to require attention, because correct identification requires the binding of two features, i.e., colour and size. Despite involving selective attention, search for such stimuli has been shown to be quite efficient (e.g., Nakayama & Silverman, 1986; Wolfe, 1998; Wolfe et al., 1989). According to Guided Search, this efficiency is due to the fact that preattentive colour processing would guide attention toward red items while – at the same time – preattentive size processing would guide attention toward small items.
More generally, attentional deployment is said to be guided by an “activation map”, which represents a weighted average of bottom-up salience and top-down guidance (Wolfe, Horowitz, Palmer, Michod, & Van Wert, 2010). The hypothetical activation map is based on a limited set of basic feature dimensions (Wolfe & Horowitz, 2004), in which local contrasts give rise to bottom-up, stimulus-driven salience. Top-down, goal-driven guidance is assumed to be based on a limited vocabulary of categorical representations (Wolfe, Friedman-Hill, Stewart, & O’Connell, 1992). The mechanism for assigning weights to some signals but not to other signals (such as irrelevant singletons) is still a matter of contention (Bacon & Egeth, 1994; Lamy & Egeth, 2003; Lamy & Tsal, 1999; Rauschenberger, 2003; Theeuwes, 1991; Yantis, 1993). Due to imperfection of weight-adjusting and the internal noise in the visual system, search is only moderately efficient, with simple items being processed at a rate of 20–40 ms per item (Wolfe et al., 2010).

According to the latest version of Guided Search (GS 4.0; Wolfe, 2007), object recognition does not follow a strictly serial or parallel model. It instead follows an asynchronous diffusion process (Ratcliff, 1978; Ratcliff, 2006). Specifically, when attention is deployed to each item, the system begins to accumulate information about that item. If that information reaches a target or distractor threshold, the system generates a target-present response or rejects that item as a distractor, respectively. Attentional deployment to the next item can begin before the identification of the previous item is completed (Wolfe, 2007; Wolfe et al., 2010). The number of items that can be selected for identification at the same time is estimated to be on the order of four, which is consistent with capacity estimates for visual working memory (Cowan, 2001; Luck & Vogel, 1997).

1.2.3. Integrated priority

Most prominent theories of attentional control describe the mechanisms for attentional selection in the context of a dichotomy between top-down (goal-driven or endogenous) and bottom-up (stimulus-driven or exogenous) control (Corbetta & Shulman, 2002; Desimone & Duncan, 1995; Egeth & Yantis, 1997; Folk et al., 1992; Itti & Koch, 2000; Jonides, 1981; Kastner & Ungerleider, 2000; Posner, 1980; Posner & Petersen, 1990; Theeuwes, 1994a,b; Wolfe et al., 1989). Despite the ubiquity of this
theoretical dichotomy, a growing number of studies report cases in which attentional selection cannot be explained based on physical salience or current goals. These cases can be divided into two broad classes of selection history and reward history (Awh, Belopolsky, & Theeuwes, 2012).

Selection history

This class of studies includes cases in which recent history of attentional selection influences subsequent selections, even when such selection-history effects are unrelated to the observer’s current goals or the physical salience of the stimuli. A classic example of such inter-trial priming effects was reported by Maljkovic and Nakayama (1994), who found that when observers searched for a “pop-out target” – defined by a unique feature such as colour or spatial frequency – searching for the same feature was more efficient on subsequent trials. Critically, such priming of pop-out occurred even when it was inconsistent with the observer’s goal to select a different feature.

In a similar vein, Theeuwes and Van der Burg (2011) found that when the search display contained two equally salient colour singletons, observers could not use advance cues to prevent an interference effect from the distractor singleton. The interference was prevented only on trials when the selected feature matched the feature selected on the preceding trial. These findings, together with the results from other studies of priming of pop-out (Hillstrom, 2000; Kristjánsson, Wang, & Nakayama, 2002; Maljkovic & Nakayama, 1996; Wang, Kristjánsson, & Nakayama, 2005), confirm that automatic inter-trial priming effects can exert strong attentional biases that are independent from observer’s current goals. Such history-driven selection may confound the effects of goal-driven selection when pure versus mixed-block designs are used. For example, some studies control for the effects of physical salience by presenting the same stimuli in different contexts, e.g., by comparing blocks of trials in which the target has a high probability of being red and blocks of trials with a low probability of a red target (Geyer, Müller, & Krummenacher, 2008; Müller, Geyer, Zehetleitner, & Krummenacher, 2009; Wolfe, et al., 2003). Under these circumstances, selection-history effects confound the goal-driven effects since both are affected by the blocked variable (Awh et al., 2012).

To distinguish the effects of history-driven selection and goal-driven selection, Theeuwes, Reimann, and Mortier (2006) presented informative cues regarding the
feature of the upcoming target singleton, but varied the cued feature randomly from trial to trial. For example, if the word ‘red’ was presented as a cue on a given trial, observers knew that there was 80% probability that the upcoming target would be a red circle. Critically, the advance cue had no beneficial effect on either search efficiency or perceptual sensitivity. This indicated that, in certain cases, goal-driven effects can be eliminated if the experimental design controls for history-driven effects.

Similar confounds might have vitiated studies of feature-based attention that have reported amplification of stimulus-evoked responses for stimuli that match the observer’s ‘top-down’ attentional set for a nonspatial feature (Saenz, Buracas, & Boynton, 2002; Serences & Boynton, 2007; Zhang & Luck, 2009). Since these studies manipulated the target-defining feature in a block design, the potential effects of goal-driven selection and history-driven selection are confounded. These considerations challenge the conventional dichotomy that considers goal-driven control to be synonymous with top-down control. Since inter-trial priming effects can be independent from the observer’s current goals and the physical salience of the stimuli, it has been suggested that selection history be added to the taxonomy of attentional control as a third category, next to goal-driven and stimulus-driven control (Awh et al., 2012).

**Reward history**

This class of studies includes cases in which attentional selection is biased toward items previously associated with reward, even when such reward-history effects are unrelated to the observer’s current goals or the physical salience of the stimuli. A growing number of studies have documented biases in attentional selection of previously rewarded stimuli, even when the observers did not receive explicit instructions (e.g., Della Libera & Chelazzi, 2009; Kiss, Grubert, Petersen, & Eimer, 2012; Kristjánsson, Sigurjónsdóttir, & Driver, 2010; Navalpakkam, Koch, Rangel, & Perona, 2010; Peck, Jangraw, Suzuki, Efem, & Gottlieb, 2009; Raymond & O’Brien, 2009; Seitz, Kim, & Watanabe, 2009; Shuler & Bear, 2006).

Interestingly, neural studies of reward processing have revealed a direct connection between reward and attention: the activity in the lateral intraparietal sulcus (IPS) area, which is known to play a critical role in spatial orienting of attention (e.g., Bisley, 2011; Bisley & Goldberg, 2010; Goldberg, Bisley, Powell, & Gottlieb, 2006;
Gottlieb, Kusunoki, & Goldberg, 1998), has been found to be directly involved in reward processing (Dorris & Glimcher, 2004; Louie, Grattan, & Glimcher, 2011; Sugrue, Corrado, & Newsome, 2004). Moreover, the reward that observers experience when they identify the target correctly may underlie the bias in attentional selection of features or locations that were attended previously (Nakayama & Martini, 2011). Based on these findings, it has been suggested that reward-induced selection be added to the taxonomy of attentional control (Awh et al., 2012).

Similar to selection history, several studies have reported dissociations between the effects of reward history and the observer’s current goals. For example, Hickey, Chelazzi, & Theeuwes (2010) assigned a high or a low monetary reward to correct identification of a shape-singleton target in the presence of a colour-singleton distractor in the additional-singleton paradigm. Hickey et al. found that reward induced an automatic selection bias for the rewarded colour, even when the reward history opposed the observer’s current goals. Further evidence for a dissociation between reward history and the observer’s current goals was obtained by Anderson, Laurent, & Yantis (2011a,b), who used pre-training to establish high and low monetary rewards for two particular colours of the target. Anderson et al. found that a learned reward biased the selection toward previously rewarded features automatically and independently from the observer’s current goals.

**Integrative framework**

Based on the evidence regarding the role of selection history in attentional control and its dissociation from observer’s current goals and the physical salience of the stimuli, Awh et al. (2012) proposed an integrative framework to study attentional control. This framework is based on the notion of a “priority map” suggested previously by several researchers (Bisley, & Goldberg, 2010; Fecteau & Munoz, 2006; Itti & Koch, 2001; Wolfe et al., 1989).

According to Awh et al. (2012), the effects of three distinct types of selection biases converge to build an integrated priority map: (i) Current goals that reflect the observer’s voluntary attentional selection at the current moment; (ii) Selection history that encompasses both selection and reward history, as well as other lasting effects of the observer’s past experience (Chun & Jiang, 1998; Umemoto, Scolari, Vogel, & Awh,
Importantly, such selection-history effects can be inconsistent with the observer’s current goals (e.g., Anderson et al., 2011a,b; Hickey et al., 2010; Maljkovic & Nakayama, 1994; Theeuwes & Van der Burg, 2011); (iii) Physical salience that refers to the physical properties of the stimuli that can bias attentional selection independently from the observer’s current goals (Egeth & Yantis, 1997; Itti & Koch, 2000; Nothdurft, 1993). An important contribution of this model is to emphasize the distinction between the active effects of the observer’s current goals and the enduring effects of selection history, which are conventionally labeled under the umbrella term ‘top-down’ factors in attention research.

1.3. ERP indices of selection in visual search

Researchers have used event-related potentials (ERPs) in conjunction with behavioural measures to study the neurophysiological correlates of attentional selection and to determine whether salient stimuli capture attention. ERPs reflect moment-to-moment changes in postsynaptic potentials that are related to sensory, cognitive, and motor events (Luck, 2005). Stimulus-driven ERPs can be measured even when participants make no overt response to the eliciting stimulus, making the ERP method ideally suited for tracking the processing of task-relevant and irrelevant singletons in the visual field. Given the lateralized organization of the visual system, most ERP studies of visual search have focused on event-related lateralizations (ERLs), which are isolated by comparing ERP waveforms recorded contralateral and ipsilateral to the location of stimuli of interest. By definition, an ERL component is a spatially specific neural response to a particular sensory or cognitive event such as the onset of a search array. These spatially specific responses may reflect processing at a variety of stages, ranging from early sensory stages (e.g., contralateral P1; Luck & Hillyard, 1994a) to later response-selection stages (e.g., lateralized readiness potential, LRP; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988).

1.3.1. The N2pc

Most ERP studies of attention capture have focused on a component of the visual ERPs that is known to reflect the selection of items in visual search. This
component – known as the N2 posterior contralateral (N2pc) – is apparent in the ERPs recorded over lateral occipital scalp regions, approximately 175–300 ms after the onset of a search display containing a task-relevant singleton. During that time interval, the ERP waveforms recorded contralateral to the (presumably attended) singleton are more negative than the ERP waveforms recorded ipsilateral to that item. Items that resemble the task-relevant singleton also elicit this N2pc, and when attention shifts rapidly to a nontarget on one side of fixation and then to a target on the other side, the N2pc shifts from one side of the scalp to the other, enabling researchers to track attention in space (Woodman & Luck, 1999, 2003).

The scalp-recorded N2pc shares many characteristics of the attention effects that have been observed at the level of the individual neuron in primate visual cortex (cf. Chelazzi, Duncan, Miller, & Desimone, 1998; Chelazzi, Miller, Duncan, & Desimone, 1993). For example, the N2pc and the single-cell attention effects begin at the same time, are larger for difficult discrimination tasks than for simple detection tasks (Luck, Girelli, McDermott, & Ford, 1997), and are larger when distractors are near the target than when they are far away (Boehlers et al., 2011; Luck et al., 1997). These similarities suggest that the N2pc reflects, at least in part, the same attention mechanism that has been hypothesized to underlie the single-unit attention effects (Luck et al., 1997; Luck & Hillyard, 1994b). In particular, both the N2pc and the single-unit effects have been ascribed to an attentional filtering process that resolves ambiguities in neural output when multiple items fall within a neuron’s receptive field (ambiguity-resolution theory; Luck et al., 1997). Theoretically, filtering can involve enhancement of the attended item’s representation, suppression of the unattended items’ representations, or both (LaBerge, 1995). Unsurprisingly, the N2pc has been linked to each of these theoretical outcomes. Several early results linked the N2pc to suppression of unattended items (Luck et al., 1997; Luck & Hillyard, 1994b), but other results suggest that the N2pc reflects target enhancement rather than distractor suppression (Eimer, 1996; Mazza, Turatto, & Caramazza, 2009). Recent work from our lab has shown that the N2pc is composed of two subcomponents, one tied to distractor suppression (the distractor positivity, PD), and the other tied to target processing (the target negativity, NT) (Hickey, Di Lollo, & McDonald, 2009).
Figure 1 illustrates the stage at which the N2pc might occur in a search task involving the additional-singleton paradigm. After preattentive processing of basic visual features and salience, the location of the most salient item is selected (spatial selection stage). The attention-filtering process thought to drive the N2pc then ensues to resolve the features of the object at the attended location (filtering stage). This sequence is consistent with recent evidence that the N2pc is associated with the processing of objects, but not empty locations, in the search display (Woodman, Arita, & Luck, 2009). Once the object features are resolved, the item can be identified as being the target or a distractor. If the attended item is identified as a distractor, the attended location is inhibited to enable a shift of attention to a new location (e.g., that of the next most salient item on the saliency map). If the attended item is identified as the target, further processing is done to discriminate the orientation of the line inside the target shape and then execute the appropriate manual response.

1.3.2. Beyond the N2pc

Several additional ERL components have been associated with visual search. As noted above, irrelevant distractors sometimes elicit a contralateral positivity called the P0 in the time range of the N2pc. This P0 can be isolated using displays containing a lateral distractor and a midline target (Hickey et al., 2009). In this case, attending to the midline target will not result in any lateralized ERP (Woodman & Luck, 2003), thereby making it possible to attribute lateralized ERP activities to the distractor. Whereas the P0 occurs in discrimination tasks, it was found to be absent in a less demanding detection task (Hickey et al., Experiment 3). The P0 is not typically observed in the reverse display configuration – that is, when the target is lateralized and the distractor is on the midline – suggesting that it reflects selective processing of the distractor (Hickey et al., 2009; see also Hillimire, Mounts, Parks, & Corbalis, 2011). Hickey et al. proposed that the P0 reflects suppression of an irrelevant, but potentially distracting, stimulus. Similar proposals have been made about distractor positivities that follow the N2pc time range (Hillimire et al., 2011; McDonald, Green, Jannati, & Di Lollo, 2012).

Early contralateral positivities preceding the N2pc have also been reported in several visual-search studies. These early positivities have been associated with low-level sensory processes (Luck & Hillyard, 1994a), preattentive identification of salient
featural discontinuities (Fortier-Gauthier, Moffat, Dell’Acqua, McDonald, & Jolicoeur, 2012), or suppression of an “attend-to-me” signal (Sawaki & Luck, 2010). One early positivity appears to be related to the stimulus-driven $P1$ (75–125 ms), which is sometimes larger contralateral to the location of a singleton than ipsilateral to it (Luck & Hillyard, 1994a). Both target and nontarget singletons can elicit this lateralized $P1$ in fixed-feature search, but Luck and Hillyard found that merely swapping the singleton and nonsingleton features eliminated the lateralized $P1$ effect. Based on this finding, they concluded that the lateralized $P1$ is due to differential refractoriness of neurons responding to the nonsingletons (fatigued) and those responding to the singleton (less fatigued) in fixed-feature tasks.

![Figure 1. Hypothetical sequence of processes in additional-singleton search is shown, based on the salience-driven selection account. Here, selection is considered to take place when information at one location is transferred from the preattentive stage to the attentive stage for further processing (cf. Theeuwes, 2010). Four lateralized ERP components have been associated with specific processing stages (see text for details).](image)

A similar, perhaps slightly later, contralateral positivity associated with visual search has been labeled the $Ppc$ ($Positivity$, $posterior$ $contralateral$; Fortier-Gauthier et al., 2012; Leblanc, Prime, & Jolicoeur, 2008). The $Ppc$ is typically found over the lateral
occipital scalp after the P1 peak, in the time interval of the subsequent N1 (140–190 ms). Like the contralateral P1 effect, the Ppc is elicited by both target singletons and nontarget singletons and has been reported primarily in fixed-feature search tasks. Thus, on initial consideration, the Ppc also seems to be tied to low-level sensory processes such as refractoriness. One recent finding is difficult to reconcile with the sensory-refractoriness account of the Ppc, however: The Ppc can be elicited by a centrally presented stimulus used to cue recollection of a multi-item display presented 1400 ms earlier (Fortier-Gauthier et al., 2012). In this case, the Ppc is found contralateral to a lateral singleton in the previous display, regardless of whether that singleton is to be recalled or ignored. Based on these findings, Fortier-Gauthier et al. proposed that the Ppc might be a spatial index linked to a representation of interest rather than a reflection of a perceptual discontinuity in the visual array.

Later contralateral positivities following the target N2pc have been reported recently. One of these positivities has been labeled the Ptc (Positivity, temporal contralateral; Hilimire, Mounts, Parks, & Corballis, 2009, 2010), which is typically found over the lateral temporal scalp, in the post-N2pc time range (290–340 ms). The amplitude of target Ptc has been reported to vary with the separation between target and distractor, but not with the separation between two targets. Based on these results, the Ptc has been attributed to individuation or isolation of a target subsequent to its identification (Hilimire et al., 2010). However, recent work indicated that distractors, but not targets, elicit the Ptc (Hilimire, Mounts, Parks, & Corballis, 2011). This suggests that, like the P0, the Ptc might reflect resolution of perceptual competition by distractor suppression. Interestingly, Sawaki, Geng, and Luck (2012) described a late (i.e., post-N2pc) positivity contralateral to task-relevant targets. Sawaki et al. interpreted this target positivity (or $P_T$) as a suppression-based termination of target processing.

Lastly, a late negativity called the SPCN (sustained posterior contralateral negativity) has been observed after the N2pc time interval, beginning approximately 400 ms after stimulus onset (Jolicoeur, Brisson, & Robitaille, 2008). Like the N2pc, the SPCN is a more negative ERP contralateral to an attended singleton than ipsilateral to it; however, the SPCN lasts considerably longer than the N2pc and is more likely to occur in discrimination tasks than in simple detection tasks (Mazza et al., 2009). The SPCN is hypothesized to occur after the attentional-filtering stage (indexed by the N2pc) and to
reflect the active maintenance of target information in visual short-term memory (VSTM; Corriveau et al., 2012; Jolicoeur et al., 2008; Luria, Sessa, Gotler, Jolicoeur, & Dell’Acqua, 2010; Vogel & Machizawa, 2004). In compound-search tasks, this active maintenance might be associated with the identification of the relevant stimulus features (e.g., orientation of the line inside the target shape; Mazza, Turatto, Umiltà, & Eimer, 2007).

These ERP indices will be used in the context of various visual-search tasks including variants of additional-singleton search (Chapter 1), pop-out search (Chapter 2), and single-item search task (Chapter 3). The goal is to track the successive stages of processing of target and distractor singletons in order to assess the evidence for salience-driven selection and the alternative theoretical perspectives.
Chapter 2.

Salience-driven capture by fixed-feature and variable-feature distractors

2.1. Introduction

To date, most ERP studies of attention capture have focused on the N2pc component. In one of the first studies of this kind, Hickey, McDonald, and Theeuwes (2006) recorded ERPs in a mixed-feature variant of the additional-singleton paradigm. Participants searched for a target shape singleton that was often accompanied by a salient-but-irrelevant colour singleton. Two main results were taken as strong evidence for automatic attention capture. First, when the target was positioned on the vertical midline (so as not to elicit lateralized ERPs), a lateral distractor was found to elicit the N2pc. This distractor N2pc demonstrated that attention was deployed directly to the distractor, at least on a portion of trials. Second, when the two singletons were presented on opposite sides of fixation, the ERP recorded over the lateral occipital scalp was initially more negative contralateral to the distractor and subsequently became more negative contralateral to the target. In other words, an N2pc “flip” was observed, with the distractor N2pc preceding the target N2pc. Hickey et al. regarded this N2pc flip as evidence that observers attended to the salient-but-irrelevant singleton before attending to the target.

Although the distractor N2pc clearly showed that attention was deployed to the salient distractor, the evidence for the salience-driven selection theory remains equivocal for two reasons. First, the original ERP evidence for salience-driven selection is not as conclusive as it was once believed. A follow-up study that included the data from Hickey et al.’s (2006) Experiment 2 (along with data from 26 additional participants) revealed that the N2pc flip reported by Hickey et al. was due to noise in the ERPs (McDonald et
al., 2013). In fact, there was no evidence suggesting that the distractor N2pc preceded the target N2pc in any of the ERP waveforms. Rather, the target and distractor N2pc waves occurred in the same time range, suggesting that attention was oriented directly to the target on some trials and to the distractor on other trials. McDonald et al. (2013) tested this option in an RT-based analysis of the ERPs. Specifically, they subdivided trials into fast-response and slow-response subsets, depending on whether the RT was shorter or longer than the median RT for that display configuration, and averaged ERPs separately for those subsets. This approach was based on the assumption that orienting attention initially to the target would lead to fast responses whereas orienting attention initially to the distractor would lead to slow responses. Consistent with this assumption, only a target N2pc was in evidence on fast-response trials, whereas a distractor N2pc was obtained on slow-response trials. The results from the fast-response trials demonstrated that attentional filtering occurred at the location of the target with no earlier attentional filtering at the distractor location. In fact, the distractor elicited a P3 on fast-response trials, suggesting that the distractor was suppressed on those trials. Such findings provide no evidence for the salience-driven selection theory outlined above.

Second, as noted earlier, the distractor interference obtained in the mixed-feature search task cannot be ascribed to automatic capture alone, because it reflects some combination of attention capture and increased attentional dwell time. In fact, according to Theeuwes (2010), the bulk of the distractor interference may actually reflect the time required to determine whether the attended stimulus is the target or a distractor (i.e., the dwell time). Moreover, in the mixed-feature task, participants might attend to the distractor only when that stimulus served as the target on the previous trial (cf. Pinto, Olivers, & Theeuwes, 2005). This can occur because the target and distractor features are swapped randomly across trials in Theeuwes’ (1991) original mixed-feature variant of the additional-singleton paradigm.

Whereas the distractor interference effects obtained in the mixed-feature task may reflect increased attentional dwell time as well as capture, the interference effects obtained in the fixed-feature task are believed to be pure measures of capture (because there is very little attentional dwell time; Theeuwes, 2010). For this reason, it is necessary to investigate the ERP correlates of attention capture in the fixed-feature variant of the additional-singleton paradigm. This has been done in a few recent studies.
The first study by Schübo (2009) was based on the Theeuwes (1992) paradigm, in which participants searched for a shape singleton and attempted to ignore a more salient colour singleton (and vice versa). The singletons were never presented on the vertical meridian, and thus it was not possible to isolate a distractor N2pc. Instead, Schübo examined how the presence of the salient distractor affected the target N2pc (relative to distractor-absent trials) and looked for an N2pc flip when target and distractor were on opposite sides of fixation. Two main results emerged from this study. First, no N2pc flip was in evidence; when target and distractor were on opposite sides, the N2pc was seen contralateral to the (less-salient) target only. Second, the target N2pc was smaller when a contralateral distractor was present than when the distractor was absent. Based on these findings, Schübo concluded that attention was deployed initially to the distractor on some trials, but not reliably enough to produce an N2pc flip (see also Theeuwes, 2010).

Wykowska and Schübo (2010, 2011) reached different conclusions in a pair of subsequent studies that combined fixed-feature visual search with a subsequent probe detection (or orientation discrimination) task. On each trial, a search display containing a target shape singleton, distractor colour singleton, both, or neither was presented briefly (50 or 100 ms) and was followed by a single probe stimulus. Participants responded first to the probe and then indicated whether the search target was present in the first display. ERPs to the search displays revealed a target N2pc but no distractor N2pc, suggesting that attention was deployed only to the target. Importantly, however, the target N2pc occurred later when the distractor was on the opposite side than when it was on the same side of fixation. Wykowska and Schübo suggested this delay might reflect a nonspatial filtering cost (cf. Folk & Remington, 1998). It should be noted, however, that the delay was revealed through a quasi-distance analysis – that is, contralateral distractors delayed the target N2pc relative to ipsilateral distractors. This is an inherently spatial, rather than nonspatial, effect. Theeuwes (2010) suggested the delay might be due to a shift of attention to the distractor followed by a rapid disengagement of attention, although it is more plausible that identification of the distractor would necessarily elicit an N2pc (see Fig. 1).

In summary, the ERP evidence for the salience-driven selection theory is equivocal. Although salient distractors sometimes elicit an N2pc in mixed-feature search
tasks (Hickey et al., 2006; McDonald et al., 2013), they do not appear to elicit an N2pc in fixed-feature search tasks (Schübo, 2009; Wykowska and Schübo; 2010, 2011). However, the extant ERP studies of fixed-feature search were designed to test for an N2pc flip, not to isolate a distractor N2pc by placing the target on the vertical meridian. The lack of N2pc flip does not rule out the salience-driven selection theory, however. Indeed, it is now known that while salient distractors elicit an N2pc in mixed-feature tasks, there is no N2pc flip when target and distractor are on opposite sides (McDonald et al., 2013). Moreover, it is unclear whether the subtle distractor-interference effects on target N2pc that have been reported reflect salience-driven capture (Schübo, 2009; Theeuwes, 2010), nonspatial filtering costs (Wykowska & Schübo, 2010, 2011), or some other process.

Experiments 1 and 2 were designed to investigate selective processing of target and distractor singletons in fixed-feature variants of the additional-singleton paradigm. The fixed-feature task was used because distractor interference primarily reflects increased attentional dwell time in mixed-feature tasks and thus cannot be ascribed to capture alone (Theeuwes 2010). Unlike prior fixed-feature ERP studies, target and distractor ERLs were isolated using displays containing one lateral singleton and one midline singleton. Rather than focusing exclusively on the N2pc, isolated ERLs were used to track target and distractor processing through successive stages (see Fig. 1). Experiment 3 was designed to investigate selective processing of the two singletons in a variant of the additional-singleton paradigm with a variable-feature distractor. To avoid some of the ambiguities in interpreting the distractor-interference effect in mixed-feature search tasks mentioned in the General Introduction, the distractor never swapped its defining feature with the target.

2.2. Experiment 1

Experiment 1 was specifically designed to determine whether a salient distractor captures attention when the non-spatial features of the stimuli remain fixed throughout the experiment. Participants searched for a specific shape singleton (green circle among green diamonds) and attempted to ignore a specific distractor colour singleton (red diamond). If the salience-driven selection theory is valid, attention would be oriented to
the location of the distractor first and only then reoriented to the location of the target. Thus, when the target was presented on the vertical midline, a lateral distractor would elicit an N2pc (Hickey et al., 2006; McDonald et al., 2013). In contrast, if the contingent-capture hypothesis is valid the distractor would not elicit N2pc but may delay the target N2pc (nonspatial filtering cost; cf. Folk & Remington, 1998, 2006). Alternatively, it was possible that the distractor would be actively suppressed by the visual system, and, thus, would elicit a P0, instead of an N2pc, without necessarily delaying the target N2pc.

2.2.1. Methods

The Research Ethics Board at Simon Fraser University approved the protocols used in all the present experiments.

Participants

Forty neurologically typical volunteers from Simon Fraser University participated in this experiment after giving informed consent. The participants were either paid for their participation or received course credit. Data from three participants were excluded from analyses because of excessive blinks or eye movements. Each of the remaining 37 participants (27 women, age 19.6 ± 1.4 years, mean ± SD) reported normal or corrected-to-normal visual acuity and had normal colour vision.

Apparatus

The experiments were conducted in a dimly lit, sound attenuated and electrically shielded chamber that contains a 19-in. CRT monitor with the screen resolution set to 800 × 600 pixels. Participants sat in an adjustable chair and viewed the monitor from a distance of 60 cm. A Windows-based computer running Presentation (Neurobehavioural Systems Inc., Albany, CA, USA) controlled stimulus presentation and registered the participants' button presses. A second Windows-based computer running custom software (Acquire) controlled EEG acquisition. The acquisition computer housed a 12-bit, 64-channel A-to-D board (PCI 6071e, National Instruments, Austin, TX, USA) that was connected to an EEG amplifier system with high input impedance (SA Instrumentation, San Diego, CA, USA). Tin electrodes mounted in an elastic cap (Electro-cap International, Eaton, OH, USA) were used to record EEG.
Stimuli and Procedure

At the beginning of the experimental session, participants were presented with a brightness-matching display that consisted of a filled red rectangle (2.1° × 3°; RGB = 255, 0, 0) and a filled green rectangle (RGB = 0, 160, 0) of the same size, adjacent to each other at the center of the screen. Participants were instructed to match the brightness of the red rectangle to that of the green rectangle. Pressing the left or right mouse button increased or decreased the R-value of the red colour by 2 RGB units, respectively. The minimum and maximum brightness allowed for the red rectangle were set at RGB = 51, 0, 0, and RGB = 255, 0, 0. When the two rectangles were perceived to be equally bright, participants pressed the middle mouse button to end the current brightness-matching trial. Four brightness-matching trials were presented to each participant. The initial R-values of the red colour in the second and fourth trials were 30 RGB units lower than in their preceding trials, whereas the initial R-value of the red colour in the third trial was 30 RGB units higher than in the second trial. At the end of the fourth brightness-matching trial, the final R-values in all four trials were averaged together. This averaged value was used as the R-value of the red colour throughout the experiment. The colour of the green rectangle used in the brightness-matching procedure was used as the green colour in the subsequent visual search task (20.1 cd/m²).

All stimuli were presented on a black background (0.02 cd/m²). Search displays consist of ten objects presented equidistant (9.2°) from a central fixation point. Two of the objects were presented directly above and below fixation, and the remaining eight objects were spaced equally, resulting in four objects on each side. Each display contained nine unfilled diamonds (4.2° × 4.2°) and one unfilled circle (3.4° diameter). On half of the trials, one of the nine diamonds was red; all of the remaining objects were green. A horizontal or vertical gray line (0.3° × 1.5°) was centered within each object. Examples of search displays used in Experiment 1 are illustrated in Figure 2.

Each trial began with a fixation point appearing for 800–1,200 ms, followed by a search display that remained on screen for 100 ms after a response is registered. The participants' task was to press one of two mouse buttons with their right hand depending on the orientation of the line contained in the green circle (i.e., the target shape
singleton). Participants were instructed to respond as quickly as possible while maintaining high accuracy. They were also asked to maintain eye fixation throughout the experiment and were told that eye movements were being monitored. Each experimental block consisted of 36 trials, and each participant completed 42 experimental blocks, for a total of 1,512 experimental trials, after performing 36 practice trials. Participants were allowed to take a short break after each block.

The target shape singleton appeared at one of the eight lateral positions or one of the two positions on the vertical midline. When present, the red diamond (i.e., the distractor colour singleton) also appeared either at a lateral position or a midline position, resulting in the following display configurations: lateral target, midline distractor (T/L/Dm; 11%); midline target; lateral distractor (Tm/Dl; 11%); lateral target, no distractor (T/L/DA; 33%); lateral target, contralateral distractor (T/L/DC; 11%); lateral target, ipsilateral distractor (T/L/DI; 11%); midline target, no distractor (T/L/DA; 17%); midline target, midline distractor (Tm/Dm; 6%).

**Electrophysiological Recording**

EEG was recorded from 63 tin electrodes positioned at FP1, FPz, FP2, AF3, AF4, F7, F5, F3, F1, Fz, F2, F4, F6, F8, FC5, FC3, FC1, FCz, FC2, FC4, FC6, T7, C5, C3, C1, Cz, C2, C4, C6, T8, CP5, CP3, CP1, CPz, CP2, CP4, CP6, P9, P7, P5, P3, P1, Pz, P2, P4, P6, P8, P10, PO7, PO3, POz, PO4, PO8, O1, Oz, O2, Iz, and M1 (American Electroencephalographic Society, 1994) and five nonstandard sites inferior to the standard occipital locations. All EEG signals were referenced to the right mastoid. The horizontal electrooculogram (HEOG) was recorded bipolarly using two electrodes positioned 1cm lateral to the left and right external canthi. Electrode impedances were kept below 10 kΩ. All signals were amplified with a gain of 20,000 and a pass-band of 0.01–100 Hz (− 3 dB point; − 12 dB per octave) and were digitized at 500 Hz.

Artifact rejection and ERP averaging were performed with the Event-related Potential Software System (ERPSS; University of California, San Diego). The EEG and HEOG were segmented into 3-s epochs that started 1s before the onset of the search displays. Epochs that were associated with incorrect responses, ocular artifacts, or amplifier blocking were excluded from further analyses. Ocular artifacts were detected using a semi-automated procedure in which differences between the minimum and
maximum voltages on the HEOG channel (eye movements) and FP2 (blinks) were compared to threshold values. If the difference between the minimum and maximum voltages in an epoch exceeded the threshold for at least one type of artifact, that epoch was excluded from further analyses. Thresholds were determined by visually inspecting the continuous EEG and HEOG to determine values that would produce rejections of all clearly visible artifacts but of few artifact-free epochs. The minimum and maximum voltages were selected within a 1-s time window within the recording epoch that started 200 ms before the onset of the search display. Stringent artifact rejection criteria for ocular artifacts were used to ensure that any N2pc results could be ascribed to covert orienting of attention rather than overt movements of the eyes.

Data analyses

**Behaviour**

Median RTs were computed for distractor-present and distractor-absent trials for each participant, after excluding trials on which participants responded incorrectly, too quickly (RT < 100 ms) or too slowly (RT > 1,500 ms). A paired t test was used to assess the difference between the resulting median RTs. This was used to gauge the overall RT interference effect (distractor-present RTs vs. distractor-absent RTs). Median RTs were also computed separately for each of five display configurations of interest. Comparing RTs to targets with same-hemifield distractors and different-hemifield distractors was a means to test the hypothesis that nearby distractors cause more interference than distant distractors (Caputo & Guerra, 1998; Mounts, 2000a, 2000b).

**Electrophysiology**

ERPs and average HEOGs time-locked to the various search display configurations were computed separately based on artifact-free trials. The averaged waveforms were digitally low-pass filtered using a Gaussian finite impulse function (–3 dB point at 25 Hz) to remove high-frequency noise produced by muscle activity and external electrical sources and were digitally re-referenced to the average of the left and right mastoids. Mean ERP amplitudes within time windows of interest (e.g., centered upon the N2pc) were computed with respect to a 200-ms prestimulus interval. This interval was also used to determine the baseline of the ERPs presented in all figures. The average HEOG did not exceed 2 µV for any of the 37 participants, which suggests
that on average the eyes were within 0.3° of the fixation point throughout the artifact-free trials (see McDonald & Ward, 1999 for HEOG calibration).

The analysis focused on ERPs elicited by search displays that contained: (a) a lateral target and a midline distractor (T_L/D_M); (b) a lateral distractor and a midline target (T_M/D_L); (c) a lateral target and no distractor (T_L/D_A); (d) a lateral target and a contralateral distractor (T_L/D_C); and (e) a lateral target and an ipsilateral distractor (T_L/D_I).

The first two display configurations, each containing one lateral singleton and one midline singleton, are critical for investigating target and distractor processing in the additional-singleton paradigm because they enable isolation of N2pc to just one of the two singletons (the lateral one; Hickey et al., 2006, 2009; Woodman & Luck, 2003). The third display configuration enabled examination of target processing in the absence of a salient distractor, whereas the fourth and fifth display configurations enabled investigation of the effect of target-distractor separation (same side vs. opposite side).

For each participant, the ERP waveforms were collapsed across visual hemifields and recording hemisphere to create waveforms contralateral and ipsilateral to lateral singletons of interest. The ipsilateral waveforms were then subtracted from the contralateral waveforms, resulting in a **contralateral–ipsilateral difference waveform** for each participant.

Following the main analysis of the all-trials ERPs, target- and distractor processing were compared on fast- and slow-response trials. This RT-based analysis of ERPs was based on the idea that different sequence of processing events may occur on different trials. There are at least two sources of variability that could interfere with the constant and successful application of attentional control: (a) changes in target and distractor locations, and (b) random intermixing of distractor-present and distractor-absent trials (cf. Müller et al., 2003). Based on these sources of variability, it is plausible that suppression of the salient distractor (as indexed by the P_D) would lead to faster responses whereas failure to suppress the distractor, or even capture of attention by the distractor (as indexed by an N2pc), would lead to slower responses. It is also plausible that the distractor affected the latency or the amplitude of target N2pc only on slow-response trials, when interference should have been greatest (cf. McDonald et al., 2013). In these cases, the all-trials ERPs that reflect the algebraic summation of the waveforms elicited on fast- and slow-response trials would obscure such differences in
the processing sequence. The ERPs were averaged separately for fast- and slow-
response trials to rule out these possibilities. This RT-based ERP analysis was
performed by computing the median RT for each display configuration, separately for
each observer. Individual trials with RTs falling below or above the relevant median RT
were defined as fast-response and slow-response trials, respectively (cf. McDonald et
al., 2013).

ERP amplitudes were computed in specific time windows centered on the peaks
observed in the relevant contralateral–ipsilateral difference waveforms, relative to a 200-
ms prestimulus baseline period. The ERLs were measured at lateral occipital electrodes
(PO7 and PO8) in order to track the successive stages of processing for the lateral
singleton of interest in each configuration. Except where noted, the mean amplitudes of
the Ppc, N2pc, P1, and SPCN were measured in the 120–180 ms, 225–275 ms, 325–
375 ms, and 400–800 ms time windows, respectively. Latencies were measured as the
time at which the voltage reached 70% of the peak amplitude within the time window of
interest. This fractional peak latency was measured in the 75–325 ms interval for the
N2pc and in the 400–800 ms interval for the SPCN. Fractional peak latency measures
were based on jackknife-average ERPs rather than the individual-subject ERPs, and the
results of statistical tests were adjusted accordingly (Ulrich & Miller, 2001).

2.2.2. Results

A total of 23.5% of the trials were discarded due to EEG/HEOG artifact (15.4%),
incorrect response (5.6%), or excessively fast or slow response (2.5%). Behavioural and
ERP analyses were conducted on the remaining trials.

Behaviour

Table 1 presents the grand-average median RTs and associated distractor-
interference effects (termed delays) for distractor-present and distractor-absent trials as
well as for the specific display configurations of interest. To assess the overall distractor-
interference effect, the grand-average median RTs for distractor-present and distractor-
absent trials were compared (668 ms and 660 ms, respectively). The 8-ms difference
was statistically significant, \( t(36) = 4.46, p = .001 \). The error rates on distractor-present
and distractor-absent trials were statistically indistinguishable (5.6% vs. 5.7%, \( t < 1 \),

26
indicating that the main distractor interference effect was not due to a speed–accuracy trade-off. Next, a repeated-measures analysis of variance (RANOVA) was conducted on RTs associated with the four distractor-present display configurations of interest to determine whether the display configuration affected search times. This omnibus analysis revealed a significant main effect of Configuration, $F(3, 108) = 3.26$, $MSE = 386.62$, $p = .024$, $\eta^2_p = .08$. A planned pairwise comparison of RTs associated with the $T_U/D_I$ and $T_L/D_C$ configurations revealed that search times were longer when the two singletons were in the same visual hemifield (675 ms) than when they were in opposite hemifields (662 ms), $t(36) = 3.46$, $p = .001$.

Table 2 presents the grand-average median RTs and associated delays for distractor-present and distractor-absent trials as well as for display configurations of interest, separately for fast-response and slow-response trials. To assess the overall delay on fast-response and slow-response trials, an ANOVA was performed on the median RTs with Response Speed (Fast vs. Slow) and Distractor Presence (Present vs. Absent) as within-subject factors. Besides the main effect of Response Speed, both the main effect of Distractor Presence, $F(1, 36) = 19.06$, $MSE = 162.48$, $p < .001$, $\eta^2_p = .35$, and the interaction effect, $F(1, 36) = 13.56$, $MSE = 85.01$, $p = .001$, $\eta^2_p = .27$, were statistically significant. This indicated that the delay was larger on slow-response trials. To assess whether the overall delay was significant on fast-response trials only, the median RTs on those trials for distractor-present and distractor-absent displays were compared (585 ms vs. 582 ms). The 3-ms overall delay on fast-response trials was statistically significant, $t(36) = 2.97$, $p = .005$. The corresponding 15-ms delay on slow-response trials (787 ms vs. 772 ms) was also significant, $t(36) = 4.26$, $p < .001$. 
Table 1. Grand Averages Across Participants Of Median Response Times (In Milliseconds) For All Distractor-Present And Distractor-Absent Trials And For The Display Configurations Of Interest In Experiments 1 And 2

<table>
<thead>
<tr>
<th>Trial type/Display configuration</th>
<th>Experiment 1</th>
<th></th>
<th>Experiment 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT (SEM)</td>
<td>Delay</td>
<td>RT (SEM)</td>
<td>Delay</td>
</tr>
<tr>
<td>Distractor present</td>
<td>668 (13)</td>
<td>8</td>
<td>584 (13)</td>
<td>8</td>
</tr>
<tr>
<td>Distractor absent</td>
<td>660 (14)</td>
<td>—</td>
<td>576 (13)</td>
<td>—</td>
</tr>
<tr>
<td>Lateral target, midline distractor</td>
<td>670 (15)</td>
<td>11</td>
<td>591 (14)</td>
<td>10</td>
</tr>
<tr>
<td>Midline target, lateral distractor</td>
<td>666 (14)</td>
<td>7</td>
<td>573 (13)</td>
<td>— 8</td>
</tr>
<tr>
<td>Lateral target, no distractor</td>
<td>659 (13)</td>
<td>—</td>
<td>581 (14)</td>
<td>—</td>
</tr>
<tr>
<td>Lateral target, contralateral distractor</td>
<td>662 (13)</td>
<td>3</td>
<td>587 (13)</td>
<td>6</td>
</tr>
<tr>
<td>Lateral target, ipsilateral distractor</td>
<td>675 (14)</td>
<td>16</td>
<td>587 (13)</td>
<td>6</td>
</tr>
</tbody>
</table>

*Note.* Delay on distractor-present trials is measured in relation to the distractor-absent trials. For other display configurations, delay is measured in relation to the lateral target, no distractor configuration.

Next, to determine whether the display configuration influenced the search efficiency in both fast-response and slow-response trials, RANOVAs were conducted on median RTs for the four distractor-present display configurations of interest, separately for fast- and slow-response trials. The omnibus analysis for the fast-response trials revealed a significant main effect of Configuration, \( F(3,108) = 6.02, \) MSE = 108.06, \( p = .001, \) \( \eta_p^2 = .14. \) A pair-wise comparison revealed that on fast-response trials the RTs were significantly longer for TL/DI configuration (590 ms) than for TL/DC configuration (583 ms), \( t(36) = 3.17, \) \( p = .003. \) Similarly, the omnibus analysis for the slow-response trials revealed a significant main effect of Configuration, \( F(3,108) = 6.33, \) MSE = 640.24, \( p = .001, \) \( \eta_p^2 = .15. \) The subsequent pair-wise comparison revealed that on slow-response trials the RTs were significantly longer for TL/DI configuration (796 ms) than for TL/DC configuration (779 ms), \( t(36) = 2.41, \) \( p = .02. \)

**N2pc and PD**

First, the ERPs and ERLs elicited by the five displays of interest, averaged across all trials (all-trials ERPs), were examined. All display configurations containing a lateral target elicited an N2pc: TL/D_l, \( F(1,36) = 43.93, \) MSE = .41, \( p < .001, \) \( \eta_p^2 = .55; \) TL/D_m, \( F(1,36) = 32.30, \) MSE = .56, \( p < .001, \) \( \eta_p^2 = .47; \) TL/D_C, \( F(1,36) = 31.43, \) MSE = .62, \( p < .001, \) \( \eta_p^2 = .47; \) TL/D_l, \( F(1,36) = 21.54, \) MSE = .57, \( p < .001, \) \( \eta_p^2 = .29. \) In
contrast, no N2pc was in evidence for displays containing a lateral distractor and midline target (T_M/D_L), $F < 1$. Based on the sequence of processing events outlined in Figure 1, these results suggest that attentional filtering processes were centered upon the location of the target but not upon the location of the distractor.

Table 2. Grand Averages Across Participants Of Median Response Times (In Milliseconds) On Fast-Response And Slow-Response Trials For All Distractor-Present And Distractor-Absent Displays And For The Search-Display Configurations Of Interest In Experiment 1

<table>
<thead>
<tr>
<th>Trial type/Display configuration</th>
<th>Fast responses</th>
<th></th>
<th>Slow responses</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT (SEM)</td>
<td>Delay</td>
<td>RT (SEM)</td>
<td>Delay</td>
</tr>
<tr>
<td>Distractor present</td>
<td>585 (11)</td>
<td>3</td>
<td>787 (18)</td>
<td>15</td>
</tr>
<tr>
<td>Distractor absent</td>
<td>582 (11)</td>
<td>–</td>
<td>772 (18)</td>
<td>–</td>
</tr>
<tr>
<td>Lateral target, midline distractor</td>
<td>588 (12)</td>
<td>7</td>
<td>789 (19)</td>
<td>17</td>
</tr>
<tr>
<td>Midline target, lateral distractor</td>
<td>584 (11)</td>
<td>3</td>
<td>785 (17)</td>
<td>13</td>
</tr>
<tr>
<td>Lateral target, no distractor</td>
<td>581 (11)</td>
<td>–</td>
<td>772 (18)</td>
<td>–</td>
</tr>
<tr>
<td>Lateral target, contralateral distractor</td>
<td>583 (11)</td>
<td>2</td>
<td>779 (18)</td>
<td>7</td>
</tr>
<tr>
<td>Lateral target, ipsilateral distractor</td>
<td>590 (12)</td>
<td>9</td>
<td>796 (19)</td>
<td>24</td>
</tr>
</tbody>
</table>

Note. Delay on distractor-present trials is measured in relation to the distractor-absent trials. For other display configurations, delay is measured in relation to the lateral target, no distractor configuration.

Next, to test whether the presence or relative location of the distractor modulated the amplitude or latency of the target N2pc, separate RANOVAs were performed on the N2pc mean amplitude and fractional peak latency for the four display configurations containing a lateral target (T_L/D_M, T_L/D_A, T_L/D_C, and T_L/D_I). There was no significant difference in the N2pc amplitudes (-0.99 µV, -1.00 µV, -1.03 µV, and -0.86 µV, respectively), $F(3,108) = 1.01$, MSE = .22, $p = .39$, $\eta^2_p = .03$, or fractional peak latencies (215 ms, 224 ms, 223 ms, and 222 ms, respectively), $F < 1$. These results indicate that the distractor did not interfere with attentional filtering at the location of the target.

The ERPs were then examined separately for fast- and slow-response trials. No distractor N2pc was found on slow-response trials (T_M/D_L: 0.59 µV contralateral vs. 0.54 µV ipsilateral to the distractor), $F < 1$. To determine whether the distractor interfered with target processing, the amplitude and latency of the target N2pc were analyzed across the four lateral-target display conditions (T_L/D_M, T_L/D_A, T_L/D_C, and T_L/D_I). There was no
significant difference in the N2pc amplitudes (-0.86 µV, -0.93 µV, -1.00 µV, and -0.71 µV, respectively), \( F(3, 108) = 1.26, \text{MSE} = .45, \ p = .29, \eta_p^2 = .03, \) or fractional peak latencies, (216 ms, 228 ms, 232 ms, and 237 ms, respectively), \( F < 1, \) across these display configurations on slow-response trials.

Similar analyses of the fast-response trials revealed no distractor N2pc (contralateral = 0.74 µV, ipsilateral = 0.60 µV; Fig. 3c), \( F < 1. \) Furthermore, there was no target N2pc amplitude difference (-1.29 µV, -1.34 µV, -1.39 µV, and -1.33 µV), \( F < 1, \) and no target N2pc latency difference (219 ms, 224 ms, 213 ms, and 219 ms), \( F < 1, \) across the lateral-target display configurations. Visual inspection of the ERPs elicited by the Tm/Dl display suggested that the distractor elicited a Pd in that configuration. This was confirmed by post-hoc statistical analysis of the ERP amplitudes in the 250–300 ms interval, in which the ERP was significantly more positive contralateral to the distractor (1.32 µV) than ipsilateral to it (0.97 µV), \( F(1,36) = 5.30, \text{MSE} = .43, \ p = .027, \eta_p^2 = .13. \) On slow-response trials, however, there was no significant difference between contralateral and ipsilateral ERPs in that interval (1.11 µV vs. 0.98 µV, respectively), \( F < 1. \) These results indicate the distractor in the Tm/Dl display elicited a Pd on fast- but not on slow-response trials.

To test whether the target N2pc differed across fast- and slow-response trials, separate ANOVAs were performed on the amplitude and latency of the N2pc elicited by the Tl/Dm display. The target N2pc was larger on fast-response trials than on slow-response trials (-1.41 µV vs. -0.89 µV, respectively; see Fig. 3a, 3b, and Fig 4b), \( F(1, 36) = 6.78, \text{MSE} = .75, \ p = .01, \eta_p^2 = .16, \) but the target N2pc latency was similar across the two trial subsets (219 ms vs. 216 ms, respectively), \( F < 1. \) Similarly, the target N2pc elicited by the Tl/Da display was larger on fast-response trials than on slow-response trials (-1.03 µV vs. -0.74 µV, respectively), \( F(1, 36) = 7.36, \text{MSE} = .22, \ p = .01, \eta_p^2 = .17. \) These latter results indicate that the difference in the amplitude of the target N2pc between fast- and slow-response trials was not due to distractor interference.
Figure 2. All-trials ERPs recorded at PO7/8 in Experiment 1. Panels a–c show the ERPs elicited by displays containing only one lateral singleton, whereas panels d and e show the ERPs elicited by displays containing two lateral singletons, either on opposite sides (d) or the same side (e). The target singleton was a green circle among green diamonds. The distractor singleton (dashed diamond) was a red diamond. Negative voltages are plotted up, by convention.
Figure 3. ERPs recorded at electrodes PO7 and PO8 in Experiment 1, averaged separately for fast-response and slow-response trials.
Figure 4. ERLs from Experiment 1. Upward and downward deflections reflect negative and positive voltages contralateral to the eliciting stimulus, respectively. (a) All-trials ERLs from the five display configurations of interest. (b) ERLs for isolation displays (containing one lateral singleton and one midline singleton), separately for fast-response and slow-response trials.

Ppc

The ERLs illustrated in Figure 4 contain large deflections prior to the onset of the N2pc. The polarity of the deflection within the 120–180 ms interval was contingent upon the configuration of the display. As in the N2pc amplitude analysis, the amplitude of the Ppc was computed with reference to the lateral target, except when the target was on the midline (in which case it was computed with reference to the lateral distractor). Thus, when the two singletons were on opposite sides of fixation, ‘contralateral’ and ‘ipsilateral’
were defined with respect to the target position rather than the distractor position. The Ppc was -0.46 μV in this T_l/D_c configuration, whereas it was 0.38 μV in the T_l/D_i configuration. These opposite-polarity peaks could be interpreted in terms of a negative ERL contralateral to the target or a positive ERL contralateral to the distractor. Critically, the Ppc elicited by the three other display configurations rule out the first interpretation. Small, nonsignificant contralateral-ipsilateral differences were observed for the T_l/D_m and T_l/D_A displays, whereas a 0.41 μV positive-going Ppc was seen for the T_m/D_l display. Statistical tests revealed that the Ppc was significantly positive for the T_m/D_l and T_l/D_i displays, ps < .001, was significantly negative for the T_l/D_c display, p < .001, and was nonsignificant for the T_l/D_m display, F(1,36) = 3.27, MSE = .09, p = .08, η²_p = .08, and T_l/D_A display, F(1,36) = 1.80, MSE = .07, p = .19, η²_p = .05. To test whether the absolute amplitude of the Ppc varied as a function of the relative location of the distractor, the Ppc amplitude in the T_l/D_c condition (-0.46 μV) was compared with the reversed polarity of the Ppc amplitude in the T_l/D_i condition (-0.38 μV). There was no significant difference in the Ppc amplitudes (t < 1). These findings provide conclusive evidence that the Ppc was a positive ERL contralateral to the distractor singleton and that its absolute amplitude did not vary with the relative location of the distractor.

To determine whether the Ppc co-varied with search performance, the amplitudes of the Ppc peaks elicited on fast-response trials were compared with those elicited on slow-response trials. The analysis focused exclusively on the T_m/D_l display in order to ensure that the ERL under investigation was tied to the lateral distractor (and not to a lateral target). The mean amplitude of the Ppc in the 120–180 ms was not significantly different between fast- and slow-response trials (.50 μV vs. .38 μV, respectively), F < 1. This indicates that the Ppc was not related to the efficiency of search or target processing.

$P_T$

Most display configurations containing a lateral target seemed to elicit a contralateral positivity in the 300–400 ms time range (Figure 4). This positivity, herein called the $P_T$, was statistically significant for T_l/D_A display, $F(1,36) = 13.13$, MSE = .67, $p = .001$, η²_p = .28, and for T_l/D_i display, $F(1,36) = 5.75$, MSE = .46, $p = .02$, η²_p = .14, whereas it did not reach significance for T_l/D_m display, $F(1,36) = 2.38$, MSE = .60, $p =$
.13, \( \eta^2_p = .06 \) or for T\(_L/D_C\) display, \( F(1,36) = 3.39, \text{MSE} = .73, p = .07, \eta^2_p = .09 \). For T\(_M/D_L\) display, the contralateral and ipsilateral waveforms were indistinguishable in this interval, \( F < 1 \).

To test whether the presence or relative location of the distractor modulated the amplitude of the P\(_T\), a RANOVA was performed on the P\(_T\) mean amplitude for the four display configurations containing a lateral target (T\(_L/D_M\), T\(_L/D_A\), T\(_L/D_C\), and T\(_L/D_I\)). There was a significant difference in the P\(_T\) amplitude (0.28 \( \mu V \), 0.69 \( \mu V \), 0.36 \( \mu V \), and 0.38 \( \mu V \), respectively), \( F(3,108) = 3.08, \text{MSE} = .39, p = .03, \eta^2_p = .08 \). This result suggested that the P\(_T\) was larger for the T\(_L/D_A\) display than for the other lateral-target configurations that also contained the distractor. To test whether the relative location of the distractor affected the P\(_T\) amplitude, a RANOVA was performed on the P\(_T\) mean amplitude for the three display configurations containing a lateral target and the distractor (T\(_L/D_M\), T\(_L/D_C\), and T\(_L/D_I\)). There was no significant difference in the P\(_T\) amplitudes, \( F < 1 \). These results indicate that the P\(_T\) amplitude was reduced by the presence of the distractor, but it was not affected by the relative location of the distractor.

To test whether the P\(_T\) differed across fast- and slow-response trials, separate ANOVAs were performed on the amplitude of the P\(_T\) elicited by T\(_L/D_A\) and T\(_L/D_M\) displays. The amplitudes of P\(_T\) elicited by the T\(_L/D_A\) display on fast-response and slow-response trials were comparable (0.76 \( \mu V \) and 0.63 \( \mu V \), respectively), \( F(1, 36) = 1.18, \text{MSE} = .30, p = .28, \eta^2_p = .03 \). Similarly, the P\(_T\) elicited by the T\(_L/D_M\) display did not significantly differ between fast- and slow-response trials (0.37 \( \mu V \) and 0.19 \( \mu V \), respectively), \( F < 1 \). These results indicate that there was no relationship between the P\(_T\) amplitude and the efficiency of the search.

**SPCN**

The ERPs once again became more negative contralateral than ipsilateral to the target in the SPCN time interval. The SPCN was in evidence for each display containing a lateral target, \( ps < .001 \), but it was absent for the T\(_M/D_L\) display, \( F < 1 \). The absence of the SPCN for the T\(_M/D_L\) display supports the conclusion that the SPCN reflects selective processing of the target.
To test whether the presence or relative location of the distractor influenced the amplitude or latency of the target SPCN, separate RANOVAs were performed on the SPCN mean amplitude and fractional peak latency for the four display configurations containing a lateral target (T_L/D_M, T_L/D_A, T_L/D_C, and T_L/D_I). There was no significant difference in the SPCN amplitudes (-0.55 μV, -0.50 μV, -0.54 μV, and -0.42 μV, respectively), $F < 1$, or latencies (634 ms, 681 ms, 613 ms, and 706 ms, respectively), $F(3, 108) = 1.19$, $p = .32$.

To test whether the SPCN was affected by the response speed, the amplitude and latency of the SPCN elicited by the T_L/D_M display were compared across fast- and slow-response trials. The target SPCN was smaller on fast-response trials than on slow-response trials (-0.47 μV vs. -0.68 μV, respectively; see Fig. 3a and 3b), $t(36) = 2.11$, $p = .042$, but the difference in the latency of target SPCN between the two trial subsets (700 ms vs. 662 ms, respectively) was not significant, $t < 1$. The larger SPCN on slow-response trials could be due to distractor’s occasional access to VSTM, probably due to an inability to suppress the distractor location (as evidenced by the absence of P_D on slow-response trials).

2.2.3. Discussion

As in prior studies using the fixed-feature variant of the additional-singleton paradigm, a salient colour singleton resulted in a small, but significant, delay in the search for a known shape singleton. Such RT interference has been attributed to two different mechanisms: salience-driven capture of attention (Theeuwes, 1992, 2010) and nonspatial perceptual filtering (Folk & Remington, 1998). The results of the RT analysis appear to be at odds with nonspatial filtering. Whereas nonspatial filtering should be independent of the spatial relationship between target and distractor, RTs were found to be longest when the target and the distractor were in the same hemifield.

Previously, researchers have attributed increased RT interference on nearby distractor trials to an inhibitory region surrounding the attended distractor (Caputo & Guerra, 1998; Hickey & Theeuwes, 2011; Mounts, 2000a, 2000b). The general idea is that if attention were captured by the salient distractor and an inhibitory surround were established around the attended distractor location, it would take more time to redeplo
attention to a (nearby) target located within the inhibited surround than to a more distant target falling outside of the inhibitory surround. Although this is possible in theory, there are two immediate shortcomings of the inhibited-surround interpretation that need to be addressed before concluding that attention was deployed to the distractor in the present experiment. First, if the distractor captured attention, relatively large RT interference should have been evident on contralateral-distractor trials, relative to ipsilateral-distractor or no-distractor trials. As outlined in the Introduction, the salience-driven selection hypothesis holds that attention is deployed to the distractor, then rapidly disengaged from that location and redeployed to the target. Clearly, this hypothesized sequence of processing events would take more time than deploying attention directly to the target whether or not the target falls in an inhibitory surround. This was not the case in Experiment 1: Contralateral distractors caused the smallest delay in search for the target.

Second, it is possible to account for the observed RT effects without assuming that attention was deployed to the distractor location. For example, referring back to Figure 1, the target location may have been selected initially, but more time may have been required for the subsequent filtering operation when the distractor was closer to the target than when it was more distant. It is also possible that the nearby distractors mainly influenced decision or motoric stages of processing rather than early spatial selection and perceptual filtering operations. Given the very small RT interference on contralateral-distractor trials, these alternative accounts are more plausible than the inhibitory-surround account.

The ERP results help to evaluate these possibilities and to track target and distractor processing more precisely. Five important ERP results emerged from Experiment 1. First, the salient distractor never elicited an N2pc, even on slow-response trials. This indicates that the selective filtering operation did not take place at the location of the salient distractor. Second, unlike Hilimire et al.’s (2009, 2010) studies, neither the presence nor the relative location of the distractor affected the amplitude or latency of the target N2pc. This pattern of results indicates that the distractor did not interfere with the initial target selection. Third, the distractor elicited a $P_D$ on fast- but not slow-response trials, indicating that observers were able to actively suppress the salient distractor on fast-response trials. This finding, in combination with the finding that the
distractor-interference effect was smaller on fast-response trials, indicates that distractor suppression may increase the efficiency of fixed-feature search.

The fourth key ERP effect was seen prior to the onset of the N2pc. Specifically a positive-going ERL was seen contralateral to the distractor singleton – but not the target singleton – in the 120–180 ms interval. At present, the functional significance of this Ppc is unclear. Referring back to Figure 1, the Ppc may have been associated with lateral asymmetries in sensory processing (Luck & Hillyard, 1994a), stimulus salience (Fortier-Gauthier et al., 2012), distractor suppression (Sawaki & Luck, 2010), or even fleeting salience-driven spatial selection that had no effect on search performance or target selection (Theeuwes, 2010). Each of these options will be considered in Experiment 2.

The fifth and final ERP effect to be highlighted was seen in the post-N2pc time range. Specifically, a positivity was elicited contralateral to the target – but not to the distractor – in the 320–370 ms interval. One possible explanation for this PT is that, similar to the Ptc (Hilimire et al., 2009, 2010), it indexes the resolution of conflict between the target and the distractor by individuating and isolating the target after its identification. Three aspects of the present results argue against this possibility. First, unlike the Ptc reported by Hilimire et al. (2010), the PT did not vary as a function of the separation between target and distractor or the relative location of the distractor. Second, if the positivity reflected a competition-biasing or conflict resolution between the two singletons, the amplitude of the positivity should presumably correlate with search efficiency, and, therefore, should have differed between fast- and slow-response trials. Third, whereas the Ptc is seen contralateral to distractors but not targets (Hilimire et al., 2011), the PT was seen contralateral to the target but not the distractor. A more-plausible functional role for this PT is that it indexes the termination of target processing via suppression (Sawaki et al., 2012).

## 2.3. Experiment 2

In Experiment 1, participants searched for a specific shape singleton and attempted to ignore a specific distractor colour singleton. In Experiment 2, the same search displays were used, but the singletons designated as target and distractor were
reversed – that is, the colour singleton was defined as the target and the less-salient shape singleton was defined as the distractor. Presenting the identical search displays in the two experiments while reversing the roles of the two singletons allowed for a direct study of the effect of salience on the attentional processing in visual search. In regards to distractor interference, if the stimulus salience determined which of the two singletons was attended first, as postulated by Theeuwes (1991, 1992, 1994a, 2010), the interference would be observed only when the most salient object in the display was the distractor but not when it was the target. This is because when the target was the most salient item, it would always be attended first and its processing could proceed without impediment. On the other hand, if the presence of a less salient singleton distractor caused interference as well, it would strongly argue against the role of salience in generating distractor interference. Thus, Experiment 2 served as a useful benchmark for Experiment 1.

2.3.1. Methods

Participants

22 participants were drawn from the same population as Experiment 1. None had participated in Experiment 1. Data from 2 participants were excluded from analyses because of excessive blinks or eye movements. Each of the remaining 20 participants (10 women, age 20.1 ± 2.1 years, mean ± SD) reported normal or corrected-to-normal visual acuity and had normal colour vision.

Apparatus, Stimuli and Procedure

These were the same as in Experiment 1 except for the following changes. On every trial, one of the stimuli was an unfilled red diamond, which appeared at one of the eight lateral positions or one of the two positions on the vertical midline. On 50% of trials, this colour-singleton target was the only unique object in the display. On the remaining 50% of trials, an unfilled green circle (1.7° radius; a shape-singleton distractor) also appeared either at a lateral position or a midline position.
Electrophysiological Recording and Data analyses

The EEG was recorded and processed as in Experiment 1, except for the following changes. A median-split analysis was not performed because salience-driven capture was not expected on any subset of trials. The mean amplitudes of the Ppc and N2pc were measured in the 100–160 ms and 200–250 ms time windows, respectively. Fractional peak latency of the N2pc was measured in the 100–300 ms time window.

2.3.2. Results

A total of 31.7% of the trials were discarded due to EEG/EOG artifact (19.4%), incorrect response (9.6%), or excessively fast or slow response (2.7%). Behavioural and ERP analyses were conducted on the remaining trials.

Behaviour

Table 1 presents the grand-average median RTs for distractor-present and distractor-absent trials as well as for the specific display configurations of interest. To assess the overall distractor-interference effect, the grand-average median RTs were compared across distractor-present and distractor-absent trials (584 ms and 576 ms, respectively). The 8-ms difference was statistically significant, \( t(19) = 3.73, p = .001 \). The error rates on distractor-present and distractor-absent trials were statistically indistinguishable (9.7% vs. 9.5%, respectively, \( t < 1 \)), indicating that the main distractor-interference effect was not due to a speed-accuracy trade-off.

To compare the RTs between the two experiments, an ANOVA was conducted with Experiment (1 vs. 2) as a between-subjects factor and Distractor Presence (Present vs. Absent) as a within-subject factor. The main effect of Experiment was significant, \( F(1,55) = 15.93, \text{MSE} = 11366.68, p < .001, \eta^2_p = .23 \), with shorter RTs in Experiment 2 than in Experiment 1. The main effect of Distractor Presence was also significant, \( F(1,55) = 29.74, \text{MSE} = 52.56, p < .001, \eta^2_p = .35 \), with shorter RTs on distractor-absent trials. Critically, the interaction was not significant, \( F < 1 \), thereby confirming that the overall distractor interference effect was indistinguishable across the two experiments.

Next, to determine whether the display configuration affected target search times, a RANOVA was conducted on RTs associated with the four distractor-present display
configurations of interest. This omnibus analysis revealed a significant main effect of Configuration, $F(3,57) = 12.15$, MSE = 108.62, $p < .001$, $\eta^2_p = .39$. A planned pair-wise comparison of RTs associated with the T/L/D_I and T/L/D_C configurations revealed that search times were indistinguishable when the two singletons were in the same visual hemifield (587 ms) and when they were in opposite hemifields (587 ms), $t < 1$. Similarly, both T/L/D_I and T/L/D_C RTs were indistinguishable from T/L/D_A RT (581 ms), $t_s < 1$. Since the overall distractor interference effect was 8 ms, the non-significance of this 6-ms difference could be either due to a lack of power or due to a genuine absence of an effect. It should be noted that the robust overall distractor interference effect was based on a comparison between all distractor-present trials and distractor-absent trials (not limited to lateral-target configurations).

**Electrophysiology**

Figures 5 and 6 display the ERP results from Experiment 2. Figure 5 shows the grand-averaged ERPs recorded contralateral and ipsilateral to the target (or distractor, when the target was on the vertical meridian; see panel b) for the five display configurations of interest. Figure 6 displays contralateral-ipsilateral difference waveforms – which help to visualize the ERL componentry – for the all-trials analysis. All of these ERPs were recorded over the occipital scalp (electrodes PO7/8).
Figure 5. All-trials ERPs recorded at electrodes PO7/8) in Experiment 2. Panels a–c show the ERPs elicited by displays containing only one lateral singleton, whereas panels d and e show the ERPs elicited by displays containing two lateral singletons, either on opposite sides (d) or the same side (e).
Figure 6. All-trials ERLs from the five display configurations of interest in Experiment 2.

N2pc and PD

All display configurations containing a lateral target elicited an N2pc: TL/DA, F(1,19) = 34.45, MSE = 1.47, p < .001, η²p = .65; TL/DM, F(1,19) = 26.99, MSE = 2.31, p < .001, η²p = .59; TL/DC, F(1,19) = 31.04, MSE = 2.0, p < .001, η²p = .62; TL/DI, F(1,19) = 20.38, MSE = 1.82, p < .001, η²p = .52. In contrast, no N2pc was in evidence for displays containing a lateral distractor and midline target (TM/DL). For this configuration, a significant PD was observed: the mean ERP amplitude in the 200–250 ms interval was significantly more positive contralateral to the distractor (1.21 µV) than ipsilateral to it (.75 µV), F(1,19) = 15.26, MSE = .14, p = .001, η²p = .45.

Next, separate RANOVAs were performed on the N2pc mean amplitude and fractional peak latency for the four display configurations containing a lateral target (TL/DM, TL/DA, TL/DC, and TL/DI) to determine whether the presence or relative location of the distractor modulated the target N2pc. The analysis revealed a significant difference in the N2pc amplitudes (-2.50 µV, -2.25 µV, -2.50 µV, and -1.93 µV, respectively), F(3,57) = 5.71, MSE = .25, p = .002, η²p = .23. A subsequent pair-wise comparison confirmed that the N2pc was significantly larger for the TL/DC than for the TL/DI display configuration, t(19) = 3.47, p = .003. In contrast, there was no significant difference
between fractional peak latencies of the N2pc for these configurations (196 ms, 196 ms, 197 ms, and 200 ms, respectively), $F < 1$.

The target N2pc observed in Experiment 2 was compared to that observed in Experiment 1 to determine whether relative stimulus salience influences the timing or magnitude of selective target processing in fixed-feature search. The analysis was focused on one display configuration – TL/DM – for this between-experiment comparison, and 20 of the 37 participants from Experiment 1 were randomly selected in order to have equal sample sizes in the two groups. The N2pc was found to occur 28 ms earlier in Experiment 2 (196 ms) than in Experiment 1 (224 ms), $F(1,39) = 6.70$, $p = .01$. Given this latency difference, mean amplitudes of the target N2pc waves were computed in different 50-ms intervals: 225–275 ms in Experiment 1 and 200–250 ms in Experiment 2. The N2pc was found to be 1.53 µV larger in Experiment 2 (-2.50 µV) than in Experiment 1 (-0.97 µV), $F(1,39) = 8.74$, $p = .005$. In other words, the target N2pc was both earlier and larger when the target was the most salient item in the search display (Experiment 2) than when the distractor was the most salient item (Experiment 1).

**Ppc**

The Ppc was in evidence only for lateral-target displays. It was significantly positive for the TL/DM configuration, $t(19) = 4.74$, $p < .001$, the TL/DA configuration, $t(19) = 3.31$, $p = .004$, and the TL/DI configuration, $t(19) = 3.06$, $p = .006$. A positive Ppc was marginally significant for the TL/DC configuration, $t(19) = 1.74$, $p = .098$. Critically, there was no Ppc for the TM/DL configuration, $t(19) = 1.48$, $p = .16$.

A between-experiment analysis revealed that the amplitude of the Ppc elicited by the TL/DM display in Experiment 2 (0.51 µV) was no different than the amplitude of the Ppc elicited by the TM/DL display in Experiment 1 (0.35 µV), $F(1,39) = 1.29$, MSE = .21, $p = .26$, $\eta^2_p = .03$.

Visual inspection of the ERLs in Figure 6 indicated that the TM/DL display elicited an early, positive ERL contralateral to the irrelevant shape singleton, which peaked at approximately 100 ms. This was confirmed by statistical analysis: In the 90–110-ms interval, the mean amplitudes at contralateral occipital and ipsilateral occipital electrodes
were 2.99 µV and 2.55 µV, respectively. This 0.44-µV difference was found to be statistically significant, $F(1,19) = 16.41$, MSE = .12, $p < .001$, $\eta^2_p = .46$.

$P_T$

There was no target positivity in evidence in the post-N2pc time range. This might be due to an absence of a $P_T$ or due to large N2pc and SPCN waves obscuring a temporally overlapping $P_T$.

$SPCN$

The SPCN was in evidence for each display containing a lateral target, $ps < .001$, but it was absent for the $T_m/D_L$ display, $t(19) = 1.27$, $p = .22$. A between-experiment analysis revealed that the amplitude of SPCN elicited by the $T_l/D_m$ display in Experiment 2 (-0.96 µV) was not significantly different from that in Experiment 1 (-0.55 µV), $F(1,55) = 2.81$, MSE = .78, $p = .10$, $\eta^2_p = .05$.

2.3.3. Discussion

The design of Experiment 2 was nearly identical to that of Experiment 1 except the roles of target and distractor singletons were reversed. Whereas participants searched for a shape singleton in the presence of a more salient, but irrelevant, colour singleton in Experiment 1, they searched for a colour singleton in the presence of an irrelevant shape singleton in Experiment 2. From the salience-driven selection perspective, less distractor interference should have occurred in Experiment 2 than in Experiment 1 because the target was the most salient item in the display. This was not the case, however: the magnitude of the distractor-interference effect observed in Experiment 2 was on par with that observed in Experiment 1 (8 ms in each). The parity does not imply, however, that the distractor captured attention in Experiment 2. This option can be ruled out on the grounds that the distractor was less salient than the target. A plausible alternative – that the distractor failed to capture attention in Experiment 1 as well as in Experiment 2 – is evaluated in the General Discussion of Chapter 2.

A noticeable aspect of the behavioural results in Experiment 2 was the absence of systematic relationship between RTs and the relative location of the two singletons,
that was observed in Experiment 1. Based on these behavioural results, one could argue that distractor interference observed in Experiment 2 was due to nonspatial filtering costs (Kahneman et al., 1983; Folk & Remington, 1998, 2006). By this account, observers did not deploy attention to the distractor location; rather, there was a delay while observers decided which of the two locations should be attended. It should be noted, however, that this nominally nonspatial account allows for considerable spatial processing during the preattentive stage. Firstly, the visual system would likely have information about the spatial locations of the two singletons. In terms of the processing steps outlined in Figure 1, this could involve the registration of both singletons on the saliency map. Additionally, the decision to orient attention to the target might, in theory, involve enhancement of the target’s location or the suppression of the distractor’s location. The results obtained in Experiment 2 are in line with this latter possibility. Namely, the distractor in Experiment 2 elicited a PD – a lateralized ERP component believed to reflect attentional suppression of irrelevant, but potentially distracting, stimuli (Hickey et al., 2009; McDonald et al., 2013).

One of the main goals of Experiment 2 was to shed light on the Ppc, which was elicited by the colour-singleton distractor in Experiment 1. In that experiment, the Ppc bore similarity to the PD: it was a positive-going ERL elicited by an irrelevant, but potentially distracting, stimulus. Although the PD typically occurs in the N2pc interval (Hickey et al., 2009; present study) or shortly thereafter (Hilimire et al., 2011; Kiss, Grubert, Petersen, & Eimer, 2012; McDonald et al., 2013), Sawaki and Luck (2010) reported to find an early, pre-N2pc PD to a salient-but-irrelevant colour singleton. Sawaki and Luck surmised that (i) the early onset of their PD was due to the high salience of the distractor in their study, and (ii) the PD reflected suppression of a salience-driven attend-to-me signal. Accordingly, the Ppc in Experiment 1 was considered to be an early PD that prevented the distractor from capturing attention. The results of Experiment 2 disconfirmed this hypothesis. Specifically, a Ppc was elicited not by the irrelevant shape singleton but by the task-relevant colour singleton in Experiment 2. The fact that the salient colour singleton elicited a Ppc in both experiments, whether it was the distractor or the target, rules out the possibility that the Ppc reflects suppression that prevents selection of the eliciting stimulus. The pattern of results is consistent with the remaining alternatives outlined in the Discussion of Experiment 1: The Ppc may be associated with
lateral asymmetries in sensory processing (Luck & Hillyard, 1994a), stimulus salience (Fortier-Gauthier et al., 2012), or even fleeting salience-driven spatial selection that had no effect on search performance or target selection (Theeuwes, 2010).

Finally, in Experiment 2, the target N2pc was larger when the distractor was in the contralateral hemifield (T_L/D_C configuration) than when it was in the ipsilateral hemifield (T_L/D_I configuration). Although this result was unexpected from the salience-driven capture perspective (since the distractor was not expected to capture attention), it is in line with a prior speculation about the summation of opposite-polarity N2pc subcomponents (Hickey et al., 2009). Using a different fixed-feature search paradigm, Hickey et al. found a negative ERL (which was termed the target negativity, N_T) contralateral to a target stimulus and a positive ERL (the P_D) contralateral to the same stimulus when it was irrelevant to the task. As in the current experiment, the N_T and P_D were observed when one of two stimuli was positioned laterally and the other was positioned on the vertical meridian (i.e., T_L/D_M and T_M/D_L configurations). Hickey et al. speculated that when target and distractor singletons are placed on opposite sides of fixation, the N_T and P_D would sum linearly to produce the conventional N2pc. Here, a corollary of this argument can be observed: When target and distractor are placed on the same side of fixation, the N_T and P_D should again sum linearly (via volume conduction from the brain generators to the scalp), this time acting in opposition. According to this line of reasoning, the N2pc measured contralateral to the target should be smaller when the target and distractor are on the same side of fixation (T_L/D_I) than when they are on opposite sides (T_L/D_C). This is precisely what was found in Experiment 2.

2.4. Experiment 3

In Experiment 1, a fixed salient distractor failed to elicit an N2pc, but it did elicit a P_D on fast-response trials. Similar findings were obtained previously in a variant of the additional-singleton paradigm in which the shapes of target and distractor singletons swapped randomly across trials, but the colour of distractor singleton was fixed in each block (McDonald & Di Lollo, 2009). Although the distractor-interference effect in that study was larger than in Experiment 1, the distractor did not elicit an N2pc but it did elicit a P_D. Both the results obtained by McDonald and Di Lollo and those obtained in
Experiment 1 are consistent with the following proposition: when the defining feature of the singleton (i.e., its colour) is fixed, either across the entire experiment or within each block, observers are able to prevent salience-driven capture by suppressing a fixed – and thus predictable – distractor.

A question that follows naturally from these results is whether salience-driven capture occurs when the defining feature of a salient distractor, e.g. its colour, is highly variable and, therefore, unpredictable. Three main possibilities can be considered under those circumstances: (i) a variable-feature distractor may be likely to capture attention because observers are not able to set themselves to ignore or suppress a particular colour. In this case, a distractor N2pc should be in evidence; (ii) observers may be able to avoid capture by guiding their search to the subset of items that possess the relevant colour or by allotting more weight to the defining dimension of the target (shape) so as to make the target more salient than the distractor. In either case, the distractor can be filtered out passively without suppression, and no P_D should be in evidence; (iii) observers may be able to actively suppress a salient distractor singleton with an unpredictable defining feature. In this case, a P_D would be in evidence. A principal objective of Experiment 3 was to tease out these possibilities.

These scenarios should not be considered to be mutually exclusive. This is because the same processing sequence does not necessarily occur on every trial. Most prior studies of covert attention capture have assumed that observers deploy their attention to the distractor on almost all trials or on no trials. We recently showed this to be a false assumption (McDonald et al., 2013). Namely, we found that the distractor in a mixed-feature search task elicited an N2pc on fast-response trials but a P_D on slow-response trials. Similarly, studies of oculomotor capture have indicated that observers make a saccade to the distractor location only for the fastest saccades (van Zoest, Donk, & Theeuwes, 2004; van Zoest, Hunt, & Kingstone, 2010). These findings confirm that different processing events could occur in different subsets of trials. For example, it is possible that making the distractor highly variable in Experiment 3 would cause observers to deploy their attention to the distractor location on a substantial portion of trials, while still not capturing attention invariably.
Experiment 3 employed a variant of the additional-singleton paradigm with a multiple-colour distractor and a shape-singleton target. Specifically, the distractor could have one of five distinct colours, and the target’s shape could be either a diamond among circles or a circle among diamonds. Since the distractor could have one of five different colours, the distractor’s colour was rarely repeated across successive trials. Whereas the target and distractor shape swapped randomly across trials, the target and distractor colour never swapped.

The variable-feature design of Experiment 3 has important advantages over fixed-feature search task in Experiment 1. The absence of salience-driven capture in fixed-feature search does not provide conclusive evidence for goal-driven control because of an alternative explanation: the mere repetition of stimulus features across trials may automatically bias attention towards the target independently of the observer's top-down attentional set (Pinto et al., 2005). For example, always responding to a green diamond among green circles may have increased the salience of the target via bottom-up priming. Similarly, always ignoring a red circle could have reduced the salience of that distractor automatically, without a suppression that is initiated by goal-driven control. According to the salience-driven selection theory (Theeuwes, 2010), a distractor N2pc would be expected if: (1) the target features varied across trials, and, thus, target repetition occurred less frequently, leading to less consistent inter-trial priming; and (2) the distractor feature also varied across trials, leading to less consistent negative priming. Since both of these conditions were present in Experiment 3, the salience-driven selection theory would predict a consistent attention capture to the distractor location.

In sum, the design of the search task in Experiment 3 had three advantages over fixed-feature search task for examining the evidence for salience-driven selection theory: (i) since the distractor colour was unpredictable and rarely repeated across successive trials, the visual system would be less likely to devalue the distractor’s salience automatically (i.e., via negative priming); (ii) since the target shape also varied across trials, there was no consistent bottom-up priming of the target's features; and (iii) the increased inter-trial variability of the distractor's unique feature would reduce the refractoriness (fatigue) of the neurons responding to the distractor, which might have occurred in Experiment 1.
Moreover, the task in Experiment 3 had an important advantage over conventional mixed-feature search tasks (Hickey et al., 2006; McDonald et al., 2013): while the target and the distractor would swap their shapes from trial to trial, the distractor’s colour – which was its defining feature – never swapped with the target’s colour. Thus, the distractor-interference effect in this task was less likely to reflect the increased attentional dwell time at the distractor location, and, therefore, would presumably reflect a pure attention-capture effect. Considered collectively, the characteristics of the task design in Experiment 3 would enable a more direct assessment of the ERP evidence for salience-driven selection.

2.4.1. Methods

Participants

54 participants were drawn from the same population as Experiments 1 and 2. None had participated in previous experiments. Data from 9 participants were excluded from further analyses because of excessive blinks or eye movements, poor overall behavioural performance, or colour-blindness. Each of the remaining 45 participants (26 women, age 20.4 ± 2.0 years, mean ± SD) reported normal or corrected-to-normal visual acuity and had normal colour vision.

Apparatus, Stimuli and Procedure

These were the same as in Experiments 1 and 2 except the following. On every trial, the target was either a green diamond among green circles or vice versa, and it appeared at one of the eight lateral positions or one of the two positions on the vertical midline. On 50% of trials, this shape-singleton target was the only unique object in the display. On the remaining 50% of trials, one of the non-target stimuli could be either red (255, 0, 0), orange (255, 140, 0), cyan (0, 255, 255), magenta (255, 0, 255), or blue (0, 0, 255), and it also appeared either at a lateral position or a midline position. Examples of search displays used in Experiment 3 are illustrated in Figure 7.

Electrophysiological Recording and Data analyses

The EEG was recorded and processed as in Experiment 1, except for the following changes. In addition to the median-split analysis, a quartile-split analysis of
trials was performed, separately for each display configuration of interest. Except where noted, the mean amplitude of the N2pc was measured in the 225–275 ms (Tl/Dl), 250–300 ms (Tl/DA), and 275–325 ms (Tl/Dc, Tl/Dm and Tm/Dl) time windows. The mean amplitude of the Ppc was measured in the 90–140 ms time window for all displays except the Tl/Dl display, for which the Ppc amplitude was measured in the 110–160 ms time window. The fractional peak latencies of the N2pc and the Ppc were measured in the 75–350 ms and 0–150 ms time windows, respectively.

Results

A total of 42.6% of the trials were discarded due to EEG/HEOG artifact (30.1%), incorrect response (12.0%), or excessively fast or slow response (2.5%). The relatively large portion of trials discarded due to ocular artifacts was probably because of a combination of stringent artifact-rejection criteria and the presence of a highly unpredictable, salient distractor singleton in the search display. Behavioural and ERP analyses were conducted on the remaining trials.

Behaviour

Table 3 presents the grand-average median RTs for distractor-present and distractor-absent trials as well as for the specific display configurations of interest. To assess the overall distractor-interference effect, the grand-average median RTs were compared across distractor-present and distractor-absent trials (858 ms and 808 ms, respectively). The 50-ms difference was statistically significant, $t(44) = 8.19$, $p < .001$. The error rate on distractor-present trials was significantly higher than on distractor-absent trials (13.1% vs. 10.9%, respectively), $t(44) = 4.46$, $p < .001$. Since observers were both faster and more accurate on distractor-absent trials compared to distractor-
Figure 7. All-trials ERPs recorded at electrodes PO7/8 in Experiment 3. Panels a–c show the ERPs elicited by displays containing only one lateral singleton, whereas Panels d and e show the ERPs elicited by displays containing two lateral singletons, either on the same side (d) or opposite sides (e).
Table 3. Grand Averages Across Participants Of Median Response Times (In Milliseconds) For All Distractor-Present And Distractor-Absent Trials And For The Display Configurations Of Interest In Experiment 3

<table>
<thead>
<tr>
<th>Trial type/Display configuration</th>
<th>Experiment 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT (SEM)</td>
</tr>
<tr>
<td>Distractor present</td>
<td>858 (23)</td>
</tr>
<tr>
<td>Distractor absent</td>
<td>808 (23)</td>
</tr>
<tr>
<td>Lateral target, midline distractor</td>
<td>828 (21)</td>
</tr>
<tr>
<td>Midline target, lateral distractor</td>
<td>821 (22)</td>
</tr>
<tr>
<td>Lateral target, no distractor</td>
<td>779 (21)</td>
</tr>
<tr>
<td>Lateral target, contralateral distractor</td>
<td>796 (19)</td>
</tr>
<tr>
<td>Lateral target, ipsilateral distractor</td>
<td>859 (26)</td>
</tr>
</tbody>
</table>

Note. Delay on distractor-present trials is measured in relation to the distractor-absent trials. For other display configurations, delay is measured in relation to the lateral target, no distractor configuration.

present trials, the main distractor-interference effect could not be due to a speed-accuracy trade-off.

Next, a RANOVA was conducted on RTs associated with the four distractor-present display configurations of interest to determine whether the display configuration affected search times. This omnibus analysis revealed a significant main effect of Configuration, $F(3, 132) = 16.96$, $MSE = 1758.84$, $p < .001$, $\eta^2_p = .28$. A planned pairwise comparison of RTs associated with the $T_L/D_I$ and $T_L/D_C$ displays revealed that search times were significantly longer when the two singletons were in the same visual hemifield (859 ms) than when they were in opposite hemifields (796 ms), $t(36) = 5.82$, $p < .001$.

Table 4 presents the grand-average median RTs and associated delays for distractor-present and distractor-absent trials as well as for display configurations of interest, separately for fast-response and slow-response trials. To assess the overall delay on fast-response and slow-response trials, an ANOVA was performed on the median RTs with Response Speed (Fast vs. Slow) and Distractor Presence (Present vs. Absent) as within-subject factors. Besides the main effect of Response Speed, both the main effect of Distractor Presence, $F(1, 44) = 65.50$, $MSE = 1698.98$, $p < .001$, $\eta^2_p = .60$,
and the interaction effect, $F(1, 44) = 8.86, \text{MSE} = 1187.86, p = .005, \eta^2_p = .17$, were statistically significant. This indicated that the delay was larger on slow-response trials. To assess whether the overall delay was significant on fast-response trials only, the median RTs on those trials were compared across distractor-present and distractor-absent displays (712 ms vs. 678 ms). The 34-ms overall delay on fast-response trials was statistically significant, $t(44) = 6.92, p < .001$. The corresponding 65-ms delay on slow-response trials (1110 ms vs. 1045 ms) was also significant, $t(44) = 6.39, p < .001$.

Table 4. Grand Averages Across Participants Of Median Response Times (In Milliseconds) On Fast-Response And Slow-Response Trials For All Distractor-Present And Distractor-Absent Displays And For The Search-Display Configurations Of Interest In Experiment 3

<table>
<thead>
<tr>
<th>Trial type/Display configuration</th>
<th>Fast responses</th>
<th>Slow responses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT (SEM)</td>
<td>Delay</td>
</tr>
<tr>
<td>Distactor present</td>
<td>712 (22)</td>
<td>34</td>
</tr>
<tr>
<td>Distactor absent</td>
<td>678 (21)</td>
<td>–</td>
</tr>
<tr>
<td>Lateral target, midline distractor</td>
<td>711 (21)</td>
<td>41</td>
</tr>
<tr>
<td>Midline target, lateral distractor</td>
<td>700 (21)</td>
<td>30</td>
</tr>
<tr>
<td>Lateral target, no distractor</td>
<td>670 (20)</td>
<td>–</td>
</tr>
<tr>
<td>Lateral target, contralateral distractor</td>
<td>683 (20)</td>
<td>13</td>
</tr>
<tr>
<td>Lateral target, ipsilateral distractor</td>
<td>724 (23)</td>
<td>54</td>
</tr>
</tbody>
</table>

Note. Delay on distractor-present trials is measured in relation to the distractor-absent trials. For other display configurations, delay is measured in relation to the lateral target, no distractor configuration.

Next, to determine whether the display configuration influenced the search efficiency in both fast-response and slow-response trials, RANOVAs were conducted on median RTs for the four distractor-present display configurations of interest, separately for fast- and slow-response trials. The omnibus analysis for the fast-response trials revealed a significant main effect of Configuration, $F(3,132) = 17.69, \text{MSE} = 765.73, p < .001, \eta^2_p = .29$. A pair-wise comparison revealed that on fast-response trials the RTs were significantly longer for $T_L/D_I$ configuration (724 ms) than for $T_L/D_C$ configuration (683 ms), $t(44) = 6.44, p < .001$. Similarly, the omnibus analysis for the slow-response trials revealed a significant main effect of Configuration, $F(3,132) = 41.80, \text{MSE} = 1929.47, p < .001, \eta^2_p = .49$. The subsequent pair-wise comparison revealed that on
slow-response trials the RTs were significantly longer for T̄1/Dı configuration (1058 ms) than for T̄1/Dc configuration (954 ms), t(44) = 10.08, p < .001.

Electrophysiology

Figures 7, 8, and 9 display the ERP results from Experiment 1. Figure 7 shows the grand-averaged ERPs recorded contralateral and ipsilateral to the target (or distractor, when the target was on the vertical meridian; see panel b) for the five display configurations of interest. Figure 8 displays ERPs averaged separately for fast-response and slow-response trials. Figure 9 displays contralateral-ipsilateral difference waveforms for the all-trials analysis, as well as the median-split analysis. All of these ERPs were recorded at electrodes PO7/8.

N2pc and P0

First, the ERPs and ERLs elicited by the five displays of interest were examined, averaged across all trials (all-trials ERPs; Fig. 8). All display configurations containing a lateral target elicited an N2pc: T̄1/Dm, F(1,44) = 22.40, MSE = .50, p < .001, η²p = .34; T̄1/Dn, F(1,44) = 58.35, MSE = .27, p < .001, η²p = .57; T̄1/Dc, F(1,44) = 30.70, MSE = .49, p < .001, η²p = .41; T̄1/Dı, F(1,44) = 6.57, MSE = .57, p = .01, η²p = .13. In contrast, no N2pc was in evidence for the T̄m/Dd display configuration in the 225-275 ms time window, F(1,44) = 1.19, MSE = .41, p = .28, η²p = .03. Similarly, no N2pc (or P0) was in evidence in the 250-300 ms or 275-325 ms time windows, Fs < 1.

Next, to test whether the presence or relative location of the distractor modulated the amplitude of the target N2pc, a RANOVA was performed on the N2pc mean amplitude for the four configurations containing a lateral target (T̄1/Dm, T̄1/Dn, T̄1/Dc, and T̄1/Dı). There was a significant difference in the N2pc amplitudes (-0.71 µV, -0.84 µV, -0.77 µV, and -0.41 µV, respectively), F(3,132) = 3.26, MSE = .48, p = .02, η²p = .07. A planned pairwise comparison between the N2pc amplitudes for T̄1/Dc and T̄1/Dı configurations found that the N2pc was smaller when the two singletons were in the same visual hemifield (-0.41 µV) than when they were in opposite hemifields (-0.77 µV), t(44) = 1.92, p = .03.
Figure 8. ERPs recorded at electrodes PO7 and PO8 in Experiment 3, averaged separately for fast-response and slow-response trials.
Figure 9. ERLs from Experiment 3. Upward and downward deflections reflect negative and positive voltages contralateral to the eliciting stimulus, respectively. (a) All-trials ERLs from the five display configurations of interest. (b) ERLs for isolation displays (containing one lateral singleton and one midline singleton), separately for fast-response and slow-response trials.
Similarly, to test whether the presence or relative location of the distractor modulated the latency of the target N2pc, a RANOVA was performed on the fractional peak latency of the N2pc for the four configurations of interest (TL/DM, TL/D₄, TL/DC, and TL/Dᵢ). There was a significant difference between the N2pc latencies (265 ms, 249 ms, 287 ms, and 239 ms, respectively), $F(3,132) = 3.22$, $p = .02$. A planned pairwise comparison between the N2pc latencies for TL/DC and TL/Dᵢ configurations found that the fractional peak latency of the N2pc was shorter when the two singletons were in the same visual hemifield (239 ms) than when they were in opposite hemifields (287 ms), $t(44) = 4.10$, $p < .001$.

Next, the ERPs were examined separately for fast-response and slow-response trials. No distractor N2pc was in evidence for fast-response trials over the 255–285 ms time window (TM/DL: -0.63 µV contralateral vs. -0.76 µV ipsilateral to the distractor), $F < 1$. In contrast, a significant distractor N2pc was found on slow-response trials over the same time window (TM/DL: -0.36 µV contralateral vs. 0.01 µV ipsilateral to the distractor), $F(1,44) = 4.98$, MSE = .62, $p = .03$, $η^2_p = .10$.

Visual inspection of the ERPs elicited by the TM/D₄ display on fast-response trials hinted at a Pp in the 300–325 ms time window (0.76 µV contralateral vs. 0.45 µV ipsilateral to the distractor). However, the Pp was not significant on fast-response trials, $F(1,44) = 2.24$, MSE = .97, $p = .14$, $η^2_p = .05$, or even on the fastest quartile of trials, $F(1,38) = 1.43$, MSE = 1.08, $p = .24$, $η^2_p = .03$ (six subjects were excluded from the quartile-split analysis due to errors issued by the ERPSS).

**Pp**

The Pp was significantly positive for the TM/D₄, $F(1,44) = 13.23$, MSE = .24, $p = .001$, $η^2_p = .23$, TL/Dᵢ, $F(1,44) = 26.85$, MSE = .20, $p < .001$, $η^2_p = .37$, and the TL/D₄ displays, $F(1,44) = 12.69$, MSE = .05, $p = .001$, $η^2_p = .22$, significantly negative for the TL/DC display, $F(1,44) = 11.04$, MSE = .24, $p = .002$, $η^2_p = .20$, and nonsignificant for the TL/D₅ display, $F(1,44) = 1.19$, MSE = .23, $p = .28$, $η^2_p = .03$. Considered together with the Ppc results of Experiment 1, these findings provide further evidence that the Ppc is a contralateral positivity that tracks the spatial location of a salient, lateral singleton: the distractor in the TM/D₄, TL/Dᵢ, and TL/DC displays and the target in the TL/D₄ display.
To determine whether the relative location of the distractor affected the timing of the Ppc, the fractional peak latency of the Ppc was compared across TL/DI and TL/DC displays. The difference in the Ppc latencies (117 ms and 95 ms, respectively) was not significant, $t < 1$. This result indicates that the timing of the Ppc is not affected by the location of the distractor relative to the target.

Similar to Experiment 1, the amplitude of the Ppc elicited by the TM/DL display was not significantly different between fast-response and slow-response trials, $F < 1$, confirming that the Ppc is not related to the efficiency of visual search.

**SPCN**

The SPCN was in evidence for all displays containing a lateral target, $p s \leq .001$, but it was nonsignificant for the TM/DL display, $t(44) = 1.17, p = .25$. The absence of the SPCN for the TM/DL display provides further evidence for the conclusion that the SPCN reflects selective processing of the target.

To test whether the presence or relative location of the distractor influenced the amplitude of the target SPCN, a RANOVA was performed on the SPCN mean amplitude for the four display configurations containing a lateral target (TL/DM, TL/DA, TL/DC, and TL/DI). There was no significant difference in the SPCN amplitudes (-0.70 μV, -0.65 μV, -0.49 μV, and -0.65 μV, respectively), $F(3,132) = 1.09, MSE = .36, p = .36, \eta^2_p = .02$.

Similarly, to test whether the presence or relative location of the distractor influenced the latency of the target SPCN, a RANOVA was performed on the fractional peak latency of the SPCN for the TL/DM, TL/DA, and TL/DI displays (the fractional peak latency of the SPCN could not be estimated reliably for the TL/DC display, probably due to a temporal overlap between the later part of the N2pc and the earlier part of the SPCN). The difference in the SPCN latencies was marginally significant (704 ms, 624 ms, and 592 ms, respectively), $F(2,88) = 2.83, p = .06$, suggesting that the SPCN occurred earlier for the TL/DI display. This finding together with the relatively shorter latency of the N2pc for the TL/DI display suggests that when the two singletons were on the same visual hemifield, both attentional filtering at the target location and the target’s access to VSTM occurred earlier.
To test whether the SPCN was affected by the response speed, the amplitude and latency of the SPCN elicited by the T_{1}/D_{m} display were compared across fast- and slow-response trials. The target SPCN was smaller on fast-response trials than on slow-response trials (-0.51 μV vs. -0.74 μV, respectively; see Figures 8a and 8b), \( F(1,44) = 4.55, \text{MSE} = .28, p = .04, \eta^2_p = .09 \), but the difference in the latency of target SPCN between the two trial subsets (716 ms vs. 697 ms, respectively) was not significant, \( F(1,44) = 2.12, p = .15 \). It is possible that the larger SPCN on slow-response trials is due to the distractor’s occasional access to VSTM, probably following capture of attention to the distractor location (as evidenced by the distractor N2pc on slow-response trials).

### 2.4.2. Discussion

Experiment 3 used a variant of the additional-singleton paradigm, in which, as in Experiment 1, the colour-singleton distractor was more salient than the shape-singleton target. However, unlike Experiment 1, both the colours and the shapes of the two singletons were varied. The colour of the distractor singleton was chosen randomly from five different colours, and, therefore, was highly unpredictable for the observers. The shape of the target singleton alternated as a diamond among circles or vice versa. Importantly, the colours of the two singletons never swapped, but their shapes did.

The main RT interference effect (50 ms), was noticeably larger than the 20-25ms effect reported previously in fixed-feature search tasks (Theeuwes, 1992) and the 8-ms effect found in Experiment 1. According to the salience-driven selection theory, this additional interference should be attributed to an increased attentional dwell time at the distractor location, and, therefore, should result in capture of attention to the distractor location on most trials (Theeuwes, 2010). Assuming that the time needed to reorient attention from the distractor location to the target location is contingent upon distance, the largest RT interference should have been obtained for contralateral-distractor trials. This is because deploying attention to the location of the distractor, disengaging from that location, and redeploying attention to the target location should presumably take longer for contralateral distractors than for ipsilateral or midline distractors. The results of the RT analysis are inconsistent with such prediction, however. In fact, the opposite was found: the smallest RT interference was obtained when the distractor was in the contralateral visual hemifield.
The general pattern of RTs was similar to what was found in Experiment 1. There was a systematic relationship between RTs and the relative location of the two singletons: the RTs became longer as the separation between the two singletons decreased, with the longest RT found for ipsilateral-distractor trials. This pattern is inconsistent with the nonspatial perceptual filtering account (Folk & Remington, 1998, 2006), in which the spatial relationship between target and distractor should not affect the RT interference.

On the face of it, the finding that a nearby distractor caused more RT interference than a distant distractor could be attributed entirely to an interference with decision or motor stages of processing rather than perceptual-filtering stage. This account is not supported, however, by electrophysiological results discussed below, including the finding that the target N2pc was smaller for ipsilateral-distractors than for contralateral-distractor trials.

Four important ERP results emerged from Experiment 3. First, the salient distractor did not elicit an N2pc on the all-trials ERPs, but it did so on slow-response trials. This indicates that the selective perceptual filtering at the distractor location occurred on most slow-response trials, but not on fast-response trials. This finding challenges the central claim of the salience-driven selection theory, i.e., that attention is always initially captured to the location of a salient distractor singleton. Several aspects of the experimental design in Experiment 3 should have in fact facilitated capture of attention by the distractor singleton: (i) the distractor’s colour was highly variable so as to reduce the observers’ ability to predict it and set themselves to ignore or suppress it; (ii) the distractor’s colour rarely repeated across successive trials so as to minimize the selection-history effects that might have reduced the distractor salience; (iii) the target’s defining feature (shape) was alternated between two features (diamond and circle) across trials so as to reduce the bottom-up priming of target’s defining feature which would increase its salience. The finding that, despite all these characteristics, attention was not captured by the distractor singleton on most trials is inconsistent with a strong version of salience-driven selection.

These results, together with the results obtained by McDonald et al. (2013) and those obtained in Experiment 1, disconfirm the notion that attention is deployed to the
target or to the distractor singleton on all (or a vast majority) of trials. Thus, it is important to estimate how often attention is deployed to each stimulus. This has been done previously for overt (oculomotor) capture (e.g., van Zoest et al., 2004) and more recently for covert attention capture (Hickey, van Zoest, & Theeuwes, 2010; McDonald et al., 2013; the present Experiment 1). These results also challenge the idea that the processing events during a visual-search experiment strictly follow the predictions from either a stimulus-driven or a goal-driven perspective.

Second, unlike Experiment 1, the relative location of the distractor affected the amplitude of the target N2pc. Specifically, the target N2pc was smaller for T_l/D_l displays than for T_l/D_c displays. Two possible reasons can be considered for this difference: (i) this result may reflect a greater interference with the perceptual filtering of the target by an ipsilateral distractor than by a contralateral distractor. This interpretation would appear contrary to the results obtained by Luck et al. (1997), who found a larger N2pc with nearby distractors; (ii) similar to Experiment 1, a smaller target N2pc for T_l/D_l displays may be due to linear summation of the N_T and the P_D with opposite polarities. Even though there was no significant P_D in evidence for T_l/D_l displays, it is conceivable that, in T_l/D_l displays, when both singletons were closer together, i.e., a larger suppression signal was generated to prevent a larger potential interference by a nearby distractor. When linearly summed with the N_T, such a P_D would reduce the measured magnitude of the N2pc.

The latency of the target N2pc was found to be shorter for T_l/D_l displays than for T_l/D_c displays. This latency difference is questionable, however, because of the difference in N2pc amplitude for the two displays. It is possible that when two waveforms have the same onset latency but different amplitudes, the smaller one is found to have shorter fractional peak latency by virtue of having a smaller peak (cf. Luck, 2005). Assuming that the latency difference is real, the smaller, but earlier, target N2pc for T_l/D_l displays compared to T_l/D_c displays might be due to the following mechanism. While ipsilateral distractors interfered with the perceptual-filtering stage underlying the N2pc (and, thus, resulted in a smaller target N2pc), the observers might have benefited from the fact that both salient singletons were in the same visual hemifield and, therefore, were able to deploy their attention more quickly to the correct hemifield, hence the earlier target N2pc.
Third, no significant $P_D$ was obtained on fast-response trials or even on the fastest-response trials. This finding, in combination with the $P_D$ results of Experiment 1, points to the critical role of distractor predictability in the observers’ ability to suppress a salient distractor. When the defining feature (colour) of the distractor was held constant throughout the experiment (Experiment 1), the observers were able to suppress the distractor on fast-response trials and improve their search efficiency. However, when the defining feature of the distractor was highly unpredictable, as in Experiment 3, the observers were not able to actively suppress the salient – and highly unpredictable – distractor on most trials. In fact, their attention was occasionally captured to the distractor location, and some perceptual filtering of the distractor occurred, as evidenced by the distractor N2pc on slow-response trials.

Fourth, all displays containing a lateral singleton (whether the target or the distractor) elicited a contralateral positivity in the pre-N2pc time range. The absolute amplitude of the Ppc was not affected by the location of the distractor relative to the target. Moreover, the Ppc amplitude was not different between fast- and slow-response trials, and, therefore, was not related to the efficiency of visual search. This pattern of results is consistent with the Ppc reflecting asymmetrical sensory activities (Luck & Hillyard, 1994a) or representing the location of a salient item on a salience map (Fortier-Gauthier et al., 2012).
Chapter 3.

Salience-driven selection in pop-out search

3.1. Introduction

A central question in attention research regards the extent to which the process of attentional selection is automatic. Many of the studies that have addressed this issue have focused on the automaticity of attentional selection for pop-out items (e.g., Pashler, 1988). From a salience-driven perspective, such items are the most likely to capture attention because they differ from all the other items in the display in one simple feature. According to the salience-driven selection theory, upon completion of the initial preattentive analysis, sensory information regarding the location with the highest salience is transferred *automatically* to the attentive stage. This spatial selection is said to be cognitively impenetrable. In other words, it is presumed that goal-driven control cannot influence the spatial selection of the most salient location in the search display (Theeuwes, 2010). The automatic capture of attention should be even stronger if the irrelevant pop-out item is the only singleton – in any feature dimension – in the display.

Luck and Hillyard (1994a) disconfirmed this hypothesis by showing that an irrelevant pop-out item defined in a feature dimension other than the target’s dimension (an *easy non-target*) does not elicit an N2pc. This indicated that observers are able to prevent attentional selection of an irrelevant pop-out item that is defined cross-dimensionally. Luck and Hillyard also assessed the automaticity of pop-out detection by comparing a pop-out detection condition with an array-colour condition in which such detection was not required. The task in the latter condition was to discriminate the colour of the display items, regardless of whether a pop-out item was present in the display. The pop-out target elicited an N2pc but the array-colour target did not. Luck and Hillyard interpreted this finding as evidence that attentional selection in a pop-out detection task
did not occur automatically, and that there was top-down guidance over deployment of attention in visual search (see Triesman & Salto, 1990; Wolfe et al., 1989).

Considering the finding that easy non-targets in the Luck and Hillyard's (1994a) study did not elicit an N2pc, two questions can be asked. First, does goal-driven control over attentional selection of a pop-out item extend to the conditions in which an irrelevant pop-out item defined in the same dimension as the target is the only singleton in the display? It is possible that goal-driven control can avoid capture of attention by a pop-out item as long as that item is defined in a different dimension from the target. One possible mechanism for such control would be by adjusting the weights of the dimensions in which the target and the irrelevant pop-out item are defined. Namely, the attentional system could increase the weight of the target’s dimension and/or decrease the weight of the distractor’s dimension so as to make the target effectively more salient than the distractor singleton (Müller et al., 2003, 2009). This would imply that if the target and the irrelevant pop-out item were defined in the same dimension, the irrelevant singleton would be more likely to capture attention automatically.

Schübo and Müller (2009) investigated the role of top-down dimensional weighting in efficient visual search by conducting pop-out search experiments that were similar to Luck and Hillyard’s (1994a) experiments. Unlike Luck and Hillyard, however, Schübo and Müller divided the trials equally among target singleton, non-target singleton, and target-absent trials. They argued that in order to assess the role of top-down goals on selective processing of singletons, it is necessary to have the same likelihood of target and non-target trials. The ERP results showed that whether a non-target singleton captured attention or not depended on whether it was defined in the same dimension as the target singleton. This suggested that top-down dimensional weighting helps guide attention in pop-out search.

The target and non-target trials in Schübo and Müller’s (2009) study were assigned based on a local feature of the singletons that was defined either within- or cross-dimensionally. An issue that remains to be investigated is whether top-down dimensional weighting extends to the conditions in which target and non-target trials are assigned based on a global feature of the pop-out search display. Under these circumstances, if the singleton always pops out within the same local feature dimension,
observers should be unable to ignore it even when it is presented in a globally irrelevant display. This is because, according to the *dimensional weighting account*, the system sets the weight for the entire target dimension regardless of its specific defining features, thereby amplifying all feature contrast signals within that dimension (Müller et al., 2009; Schübo & Müller, 2009).

The second question regards to the timing of attentional selection: does attentional selection of a pop-out item always occur at the same time, or whether the timing of such selection can be influenced by goal-driven factors? The salience-driven selection theory critically predicts that: (i) bottom-up salience determines selection in the first 150 ms or so, and (ii) top-down guidance is possible only afterwards. If this is indeed the case, the fact that a search display containing a pop-out item is irrelevant to the observer’s goals should not influence the timing of selecting that item. In contrast, if goal-driven control can influence the timing of selection, the attentional system should be able to delay selection of a pop-out item if the observer is required to first decide whether the search display is task-relevant or not.

To address these questions, a pop-out search task was designed in which the observer had to make a *Go/No-Go decision* on each trial whether to search for an orientation pop-out target or not (Experiment 4). The decision was based on a global feature of the search display, i.e., the colour of all the items in the display. If the colour of the items was the assigned Go colour, observers were required to make a discrimination response based on the target’s length. In contrast, if the colour of the items was the No-Go colour, observers were not required to make any response. To isolate the effect of the Go/No-Go decision, a control experiment was conducted with displays identical to those used in Experiment 4, except that there was no Go/No-Go decision to be made and observers made the discrimination response on every trial (Experiment 5).

It should be noted that both the present Experiment 4 and the Experiment 3 in Luck and Hillyard’s (1994a) study used an orientation pop-out condition and an array-colour condition to investigate the automaticity of pop-out detection in visual search. Two important distinctions should be made between the two experiments, however. First, the observers in both conditions of Experiment 3 in the Luck and Hillyard’s study were always in a Go condition. This is because they were always required to make a
response, either based on the colour of the search array or the presence or absence of the pop-out item. In contrast, the observers in the present Experiment 4 had to withhold responses on some trials. Namely, they were asked to withhold their responses when the array colour was a No-Go colour. Second, the pop-out condition and the array-colour condition in the Luck & Hillyard’s study were presented in separate blocks, whereas the Go and No-Go conditions in the present Experiment 4 were randomly intermixed. Thus, there were two distinct targets defined in different dimensions and presented in separate blocks in the Luck & Hillyard’s study, whereas there was only one target defined in the same (orientation) dimension in the present Experiment 4.

Crucially, the fact that different target dimensions were defined in separate blocks in the Luck & Hillyard’s (1994a) Experiment 3 may have promoted a dimensional-weighting strategy. Namely, the observers in the array-colour condition may have reduced the weight of the orientation dimension, thereby decreasing the feature contrast signals within that dimension (Müller et al., 2009; Schübo & Müller, 2009). This dimensional weighting may have helped the observers avoid deploying their attention to the pop-out item in the array-colour condition. In contrast, such dimensional weighting would not likely occur in the present Experiment 4, in which the target was always defined in the same dimension and there were no targets associated with the randomly intermixed No-Go trials. This is because dimensional weighting is said to develop across several trials and typically at least across a separate block of trials (Müller et al., 2009). It thus remains to be investigated whether observers can avoid deploying attention to a pop-out item defined in a given dimension (e.g., orientation) when that item is occasionally task-irrelevant based on a global feature of the search array defined in another dimension (e.g., colour).

The design of the Go/No-Go search task also enables an investigation of inter-trial changes (e.g., Pinto et al., 2005) on the timing of attentional selection in visual search. Such effects can be investigated at two levels: (i) the task-relevance of the entire search display, and (ii) the low-level sensory features of the stimuli in the search display. In order to assess the inter-trial changes in task-relevance, the latency of the target N2pc on Go trials preceded by a Go trial (Go-Repeat trials) are compared with that on Go trials preceded by a No-Go trial (Go-Change trials). If the pop-out item on No-Go trials does elicit an N2pc, similar comparisons can be made between the latency of the
N2pc on *No-Go-Repeat* and that on *No-Go-Change* trials. To assess the inter-trial changes in the low-level sensory features, the latency of target N2pc on trials on which the display items had the same colour as the preceding trial (*Colour-Repeat trials*) are compared to that on trials on which the display items had changed colour from the preceding trial (*Colour-Change trials*). These comparisons help isolate the selection-history effects, both at the high level of decision-making and at the low level of sensory features, on the timing of attentional selection in visual search.

Three predictions can be tested in this paradigm. First, if selection of a pop-out item happens automatically, as predicted by the salience-driven selection theory, the pop-out item should be selected regardless of whether the search display is relevant or irrelevant to the task at hand. In other words, search displays on both Go and No-Go trials should elicit an N2pc. In contrast, if the observer’s current goals can exert control on attentional selection, the pop-out item should be selected only when the search display is task-relevant. In that case, the N2pc should not be observed on No-Go trials.

Second, if selection of a pop-out item is truly automatic, as predicted by the salience-driven selection theory, the timing of such selection should not be affected by the observer’s current goals, i.e., whether the observer is required to make a Go/No-Go decision to perform the search or not. In that case, the latency of target N2pc on Go trials in Experiment 4 should be comparable to that on all trials in Experiment 5. In contrast, if the timing of selection of a pop-out item is influenced by goal-driven factors, the target N2pc on Go trials in Experiment 4 should occur later than the target N2pc on all trials in Experiment 5.

Third, if inter-trial changes in the task-relevance of the search display influence the timing of attentional selection, as predicted by the integrated-priority theory (Awh et al., 2012), the attentional selection of the pop-out item in Experiment 4 should occur earlier on Go-Repeat trials than on Go-Change trials. In that case, the latency of target N2pc should be shorter on Go-Repeat trials than on Go-Change trials. If the pop-out item elicits an N2pc on No-Go-Repeat and No-Go-Change trials, a similar prediction can be made for the comparison between the latency of the N2pc on those two subsets of trials. Moreover, if inter-trial changes in low-level sensory features of the display items influence the timing of attentional selection, as predicted by the salience-driven selection
theory, the target N2pc in Experiment 5 should occur earlier on Colour-Repeat trials than on Colour-Change trials.

Comparing the ERLs elicited by the pop-out item on Go and No-Go trials in Experiments 4 and on all trials in Experiment 5, together with examining the inter-trial priming effects in both experiments, would allow for investigating the automaticity of attentional selection, the role of observer’s current goals, and the effects of selection history on attentional selection in pop-out search.

3.1.1. Additional ERP components

To further investigate the automaticity of attentional selection in pop-out search, three additional ERP components can be examined that are known to be involved in pop-out search (the N2b and the P2a) and in Go/No-Go tasks (the No-Go P3).

The visual N2b (also labeled the N2pb) consists of bilateral negativity over posterior sites obtained in visual target-detection tasks that occurs between approximately 180 and 300 ms post-stimulus (Simson, Vaughan, & Ritter, 1977). The N2b is typically elicited by a deviant item presented among a simultaneous array of several identical items when the deviant item is a target or when it is highly similar to the target (Luck, 2005; Luck & Hillyard, 1994a). This component is thought to reflect the stimulus categorization process, particularly for stimuli that require a response, and it is larger for less frequent targets (Lange, Wijers, Mulder, & Mulder, 1998; Luck & Hillyard, 1994a; Okita, Wijers, Mulder & Mulder, 1985; Potts & Tucker, 2001; for a review, see Wijers, Mulder, Gunter, & Smid, 1996). The latency and topography of the N2b can vary based on the defining feature of the target, indicating that the N2b reflects creation and categorization of feature-specific perceptual representations in the posterior visual areas (Harter & Aine, 1984; O'Donnell, Swearer, Smith, Hokama, & McCarley, 1997; Potts & Tucker, 2001).

The P2a (or the anterior P2) consists of bilateral positivity over prefrontal cortex that typically accompanies the N2b in visual target-detection tasks and occurs at about the same latency as the N2b (180–300 ms post-stimulus; Luck & Hillyard, 1994a; Makeig et al., 1999; Potts, Liotti, Tucker, & Posner, 1996; Potts & Tucker, 2001).
Differences in psychological responsiveness (Potts et al., 1996), latency (Wijers, Mulder, Okita, & Mulder, 1989), and laterality (Potts, 2004) suggest that the P2a and the N2b may not be the opposite poles of the same generator and probably originate from different neural generators. The N2b is believed to reflect stimulus-driven processing in posterior visual areas, whereas the P2a is believed to reflect task-related processing, particularly the evaluation of task-relevance, in the inferior prefrontal cortex (Delorme, Westerfield, & Makeig, 2007; Potts, 2004; Potts & Tucker, 2001).

The main objective in examining these ERPs in Experiment 4 is to determine whether the N2b and the P2a waves on Go and No-Go trials begin to diverge prior to the target N2pc on Go trials. Since the N2b and the P2a waves are believed to reflect stimulus categorization and task-relevance evaluation, respectively, comparing the latency at which these two waves diverge on Go and No-Go trials with the latency of the target N2pc helps evaluate the ERP evidence for salience-driven attentional selection. If the N2b and the P2a waves on Go and No-Go trials begin to diverge prior to the onset of the target N2pc, it would indicate that the processes involved in the Go/No-Go decision occur prior to the attentional selection of the pop-out item. Such pattern of results would not be consistent with an automatic attentional selection, which should occur independently from the Go/No-Go decision. In contrast, if the N2b and the P2a waves on Go and No-Go trials begin to diverge subsequent to the onset of the target N2pc, it would indicate that the attentional selection of the pop-out item occurs independently from the processes involved in the Go/No-Go decision. Such pattern of results would support the salience-driven selection theory.

The No-Go P3 activity consists of larger frontal P3 in No-Go conditions than in Go conditions, peaking around 300–500 ms post-stimulus (Eimer, 1993; Kopp, Mattler, Goertz, & Rist, 1996). The No-Go P3 activity has been found to be maximal at frontocentral sites (Fallgatter, Mueller, & Strik, 1999; Fallgatter & Strik, 1999), particularly originating from the anterior cingulate cortex (ACC; Fallgatter, Bartsch, & Herrmann, 2002; Strik, Fallgatter, Brandeis, & Pascual-Marqui, 1998). This P3 modulation has been attributed to response inhibition in the No-Go condition (Bokura, Yamaguchi, & Kobayashi, 2001; Bruin, Wijers, & Van Staveren, 2001; Pfefferbaum, Ford, Weller, & Kopell, 1985).
The main purpose of examining the No-Go P3 in Experiment 4 is to establish the occurrence of response inhibition on No-Go trials. Determining whether such inhibition occurs will be useful in interpreting the difference in N2pc latency between Go-Repeat and Go-Change trials. For example, if the target N2pc is found to occur later on Go-Change trials than on Go-Repeat trials, it can be argued that on Go-Change trials the attentional selection of the target was delayed due to the lingering effects of response inhibition on the preceding No-Go trial. Since on Go-Repeat trials no response inhibition had occurred on the preceding trial, the attentional selection could proceed more readily, and, thus, the target N2pc occurred earlier.

3.2. Experiment 4

3.2.1. Methods

Participants

24 participants were drawn from the same population as Experiments 1 to 3. None had participated in previous experiments. Data from six participants were excluded from further analyses because of excessive eye movements, blinks, or poor overall behavioural performance. Each of the remaining 18 participants reported normal or corrected-to-normal visual acuity and had normal colour vision.

Apparatus

This was the same as in previous experiments.

Stimuli and Procedure

All stimuli were presented on a black background (0.02 cd/m^2). Search displays consisted of sixteen bars (1.8° x 0.4°) placed randomly inside an imaginary rectangle (19° x 14°) at the center of the screen, with the following constraints: (i) eight bars were on the left side of the screen center, with the other eight bars on the right side; (ii) the minimum distance between two adjacent bars was 3.4°; and (iii) the minimum distance between the center of the bars and the center of the screen was 0.9°. On each trial, the bars were either all cyan (RGB = 0, 204, 255) or all yellow (RGB = 255, 255, 0). They
were also all horizontal or all vertical. One of the bars was chosen randomly to have a different orientation from the other bars (a horizontal bar among vertical bars or vice versa). This orientation singleton was also either longer (2.3° x 0.4°) or shorter (1.3° x 0.4°) than the other bars. Examples of search displays used in Experiment 4 are illustrated in Figure 10.

Each trial began with a fixation cross appearing for 600–900 ms, followed by a search display that remained on screen for 750 ms. For each participant, either cyan or yellow was assigned as the Go colour. The task was first to make a Go/No-Go decision whether to perform the visual search or not. For example, if cyan was the Go colour, the participant was asked not to make any response when presented with yellow bars. When the bars were cyan, however, the participant was asked to search covertly for the orientation singleton and perform a discrimination task based on the length of the singleton. The choice of Go colour was counterbalanced across participants, and Go and No-Go trials were randomly intermixed.

On Go trials, the participant pressed one of two mouse buttons to discriminate the length of the orientation singleton. Participants were instructed to respond as quickly as possible while maintaining high accuracy. They were also asked to maintain eye fixation throughout the experiment and were told that eye movements were being monitored. The experimental session started with 40 practice trials. Each experimental block consisted of 80 trials, and each participant completed 21 experimental blocks, for a total of 1,680 experimental trials. Participants were allowed to take a short break after every 40 trials.
Electrophysiological Recording

This was the same as in previous experiments.

Figure 10. ERPs recorded at electrodes PO7/8 in Experiment 4. The top and bottom panels show the ERPs elicited on Go trials and No-Go trials, respectively.

Data Analyses

Behaviour

Median RTs were computed for Go trials for each participant, after excluding trials on which participants responded incorrectly, too quickly (RT < 100 ms) or too slowly (RT > 1650 ms). This RT analysis was intended for a comparison between the Go trials in Experiment 4 and all trials in Experiment 5. Comparing RTs when a Go/No-Go decision was required and when such decision was not required would enable estimation of the behavioural cost of making a Go/No-Go decision in visual search.
**Electrophysiology**

The methods for averaging and measuring ERPs were similar to those in Experiment 1 except for the following changes. The ERPs were averaged separately for Go and No-Go displays. Except where noted, the N2pc amplitude and fractional peak latency were measured in the 300–350 ms and 75–350 ms time windows, respectively.

### 3.2.2. Results and Discussion

#### Behaviour

The median RT for Go trials with correct response was 623 ms. This RT will be compared with the median RT for all trials in Experiment 5.

#### Electrophysiology

Figure 10 illustrates the ERP results for Go and No-Go trials in Experiment 4. The orientation singleton elicited a significant N2pc on Go trials (0.70 µV), $F(1,17) = 21.12$, MSe = .21, $p < .001$, $\eta^2_p = .55$, but not on No-Go trials (0.23 µV), $F(1,17) = 1.62$, MSe = .31, $p = .22$, $\eta^2_p = .09$. The N2pc on No-Go trials was not significant in the 225–325 ms time window either, $F(1,17) = 2.50$, MSe = .19, $p = .13$, $\eta^2_p = .12$.

To determine the effect of inter-trial changes in goal-driven factors on the timing of attentional selection, the N2pc latency on Go-Repeat trials was compared with the N2pc latency on Go-Change trials. The observers were expected to select the singleton more readily on Go-Repeat trials. This is because having been presented with a Go trial on the preceding trial, the observers may have been ‘set’ to proceed with the visual search on the current trial. In contrast, the observers were expected to be slower in selecting the singleton on Go-Change trials due to having inhibited their search on the preceding (No-Go) trial. To test this hypothesis, the 70% fractional peak latency of the N2pc was compared on Go-Repeat trials (245 ms) and Go-Change trials (296 ms; see Figure 11). The 51-ms difference in N2pc latency was found to be significant, $t(17) = 1.98$, $p = .032$ (one-tailed). The use of a one-tailed test here is justified because we hypothesized at the outset that the N2pc would occur earlier on Go-Repeat trials. This result suggests that inter-trial changes in goal-driven factors can influence attentional selection in pop-out search.
Next, to determine the effect of inter-trial changes in goal-driven factors on the N2pc amplitude, the mean amplitude of the N2pc in the 275–325 ms time window on Go-Repeat trials (-0.68 µV) was compared with the mean amplitude of the N2pc in the 300–350 ms time window on Go-Change trials (-0.83 µV). The difference between N2pc amplitudes was not significant, $t < 1$.

Although there was no significant N2pc in evidence for all No-Go trials, it was necessary to test whether an N2pc was elicited on No-Go trials preceded by a Go trial (No-Go-Change trials). This is because on No-Go-Change trials attentional selection may have been more likely to occur due to inter-trial priming effects. Namely, since observers had attentionally selected the pop-out item on the preceding trial, they may have been ‘set’ to proceed with attentional selection on the next trial, even though it was a No-Go trial. The N2pc on No-Go-Change trials was not significant in the 300–350 ms time window (-0.33 µV), $F(1,17) = 1.94$, MSe = .49, $p = .18$, $\eta^2_p = .10$. Similarly, No-Go-Repeat trials did not elicit a significant N2pc in the same time window (-0.1 µV), $F < 1$. The ERLs elicited by the pop-out item on No-Go-Repeat and No-Go-Change trials are illustrated in Figure 12.

Figure 11. Contralateral-ipsilateral difference waveforms recorded at electrodes PO7/8 for Go-Repeat and Go-Change trials in Experiment 4. The arrows indicate the 70% fractional peak latency of the N2pc.
Figure 12. Contralateral-ipsilateral difference waveforms recorded at electrodes PO7/8 for No-Go-Repeat and No-Go-Change trials in Experiment 4. The ERLs in the N2pc time range were not significantly different from zero.

Since there were no significant ERLs elicited by the pop-out item in the N2pc time range on No-Go-Repeat and No-Go-Change trials, it was not possible to compare the fractional peak latency or the mean amplitude of the ERLs elicited on those trials.

The finding that no N2pc was in evidence for No-Go trials indicates that attentional filtering did not occur at the singleton location when a decision not to search was made. The absence of evidence for attentional selection of the singleton on No-Go trials is inconsistent with the salience-driven selection theory. This is because if attentional selection of the most salient item in the display was truly automatic, the orientation singleton should have captured attention regardless of whether that singleton was task-relevant or not.

Figure 13 shows ERPs elicited by the Go and No-Go displays in Experiment 4, particularly the P2a, the No-Go P3, and the N2b, obtained over the anterior scalp (electrode FPz), the central scalp (electrode Cz), and the medial occipital scalp (electrode Oz), respectively. The electrode for examining each component was chosen based on the topography of the component and where its amplitude was the largest.
Figure 13. ERPs recorded at electrodes FPz, Cz, and Oz in Experiment 4. The Go and No-Go ERPs began to diverge in the pre-N2pc time range, eliciting the P2a over the anterior scalp (FPz) and the N2b over the medial occipital scalp (Oz). The No-Go P3 component was prominent over the central scalp (Cz).
To determine whether the P2a and the N2b waves diverged on Go and No-Go trials, the mean amplitude of the Go and No-Go ERPs were compared over the 150–280 ms time window. The difference between the mean amplitude of Go and No-Go ERPs at the electrode FPz was significant (8.76 µV and 6.89 µV, respectively), $F(1,17) = 37.90$, MSe = .83, $p < .001$, $\eta^2_p = .69$. Similarly, the difference between the mean amplitude of Go and No-Go ERPs at the electrode Oz was significant (-1.38 µV and 0.36 µV, respectively), $F(1,17) = 19.30$, MSe = 1.40, $p < .001$, $\eta^2_p = .53$. These results demonstrate the divergence of the P2a and the N2b waves on Go and No-Go trials.

Next, to determine whether the P2a and the N2b waves had diverged on Go and No-Go trials as early as 150–200 ms, the mean amplitude of the Go and No-Go ERPs were compared over that time window. The difference between the mean amplitude of Go and No-Go ERPs over the 150–200 ms time window at electrode FPz was significant (7.73 µV and 6.38 µV, respectively), $F(1,17) = 66.34$, MSe = .25, $p < .001$, $\eta^2_p = .80$. Similarly, the difference between the mean amplitude of Go and No-Go ERPs at electrode Oz was significant (-1.93 µV and -1.06 µV, respectively), $F(1,17) = 6.47$, MSe = 1.03, $p = .02$, $\eta^2_p = .28$. These results indicate that the P2a and the N2b waves had diverged on Go and No-Go trials as early as 150–200 ms post-stimulus. In contrast, the target N2pc on Go trials had not yet occurred in that time window: the difference between the mean amplitude of contralateral and ipsilateral ERPs elicited by the target singleton on Go trials over the 150–200 ms time window at electrodes PO7/8 was not significant (-1.91 µV and -1.98 µV, respectively), $F < 1$. This pattern of results indicates that the processes involved in the Go/No-Go decision occurred prior to the attentional selection of the pop-out item.

To determine the latency at which the P2a and the N2b waves had diverged on Go and No-Go trials, the 70% fractional peak latency of the Go minus No-Go difference waveform was measured over the 75–300 ms time window at the electrodes FPz and Oz, respectively. The fractional peak latencies of the P2a and the N2b were 199 ms and 188 ms, respectively. The 11-ms difference in latency was not significant, $t(17) = 1.41$, $p = .18$. Since there was no significant difference between the fractional peak latency of the P2a and the N2b components, their latency can be estimated as the average of 199 ms and 188 ms, or approximately 194 ms. Comparing this latency with the 70% fractional peak latency of the target N2pc on Go trials (271 ms) indicates that the P2a
and the N2b waves diverged on Go and No-Go trials approximately 77 ms before the target N2pc on Go trials. These results indicate that the stimulus categorization and the evaluation of task relevance involved in the Go/No-Go decision, as indexed by the N2b and the P2a, respectively, occurred substantially earlier than the attentional selection of the target, as indexed by the N2pc. This pattern of results argues against a purely automatic attentional selection in pop-out search, according to which the selection of the pop-out item should occur regardless of its task-relevance. In contrast, these results suggest that the goal-driven factors involved in the Go/No-Go decision precede and control the attentional selection. If the pop-out item is determined to be irrelevant to the task at hand, its attentional selection is unlikely.

To determine whether the Go/No-Go decision in Experiment 4 elicited the No-Go P3 component, the mean amplitude of the Go and No-Go ERPs were compared over the 220–580 ms time window at electrode Cz (1.71 µV and 4.12 µV, respectively). The difference in the amplitude was significant, \( F(1,17) = 14.43, MSe = 3.60, p = .001, \eta^2_p = .46 \). This result indicates that the Go/No-Go task elicited the No-Go P3, suggesting that response inhibition occurred on No-Go trials. This finding is consistent with the interpretation that the later target N2pc on Go-Change trials compared to Go-Repeat trials was due to the lingering effect of response inhibition on a Go-Change trial that occurred on the preceding No-Go trial.

The rest of ERP analyses and discussion of results for Experiment 4 will be performed in comparison with the ERPs obtained in Experiment 5.

### 3.3. Experiment 5

Experiment 5 was designed to serve as an important benchmark for Experiment 4. The stimuli and procedures were identical to those in Experiment 4 except for the following. Whereas participants in Experiment 4 had to make a Go/No-Go decision on each trial whether to perform the search or not, participants in Experiment 5 performed the search and the subsequent discrimination task on every trial. If the salience-driven selection theory is valid, the latency of attentional selection of the most salient item in the display should not depend on the observer’s current goals. Thus, the singleton N2pc in
Experiment 5 should occur at approximately the same latency as that on Go trials in Experiment 4. In contrast, if a noticeable difference is observed between the N2pc latency on Go trials in Experiment 4 and that on all trials in Experiment 5, it would be inconsistent with a purely stimulus-driven selection. Moreover, if selection history effects at the low level of sensory features significantly affected the latency of attentional selection, the N2pc should occur earlier on Colour-Repeat trials than on Colour-Change trials.

3.3.1. Methods

Participants

20 participants were drawn from the same population as Experiments 1 to 4. None had participated in previous experiments. Data from two participants were excluded from further analyses because of excessive eye movements, or poor overall behavioural performance. Each of the remaining 18 participants reported normal or corrected-to-normal visual acuity and had normal colour vision.

Apparatus

This was the same as in previous experiments.

Stimuli and Procedure

These were identical to Experiment 4 except that the colour of the items in the search display was irrelevant and participants performed the discrimination task on every trial. Examples of search displays used in Experiment 5 are illustrated in Figures 10 and 14.

Electrophysiological Recording and Data Analyses

These were the same as in Experiment 4 except for the following changes. The ERPs for all trials (All-Go trials) were averaged together, because there were no Go and No-Go trials. The N2pc amplitude and fractional peak latency were measured in the 225–275 ms and 140–350 ms time windows, respectively.
3.3.2. Results and Discussion

Behaviour

The median RT for All-Go trials in Experiment 5 (570 ms) was significantly shorter than the median RT on Go trials in Experiment 4 (623 ms), $F(1,34) = 11.06$, MSe = 4637.55, $p = .002$, $\eta^2_p = .25$. Since all the other aspects were identical between the two experiments, this 53-ms RT difference indicates the behavioural cost of the Go/No-Go decision to perform the visual search in Experiment 4.

Electrophysiology

Figure 14 displays the All-Go ERPs obtained in Experiment 5. As expected, the target singleton elicited a significant N2pc (-0.63 $\mu$V), $F(1,17) = 17.98$, MSe = .20, $p = .001$, $\eta^2_p = .51$.

To answer the critical question of whether the Go/No-Go decision in Experiment 4 delayed the attentional selection of the singleton, the fractional peak latency of the N2pc on Go trials in Experiment 4 (281 ms) was compared with that on All-Go trials in Experiment 5 (219 ms; see Figure 15). This 62-ms difference in N2pc latency was significant, $t(34) = 2.87$, $p = .007$, indicating that the Go/No-Go decision in Experiment 4 delayed the attentional selection of the singleton compared to Experiment 5, i.e., when such a decision was not required. This result is inconsistent with the salience-driven selection theory. This is because if the selection of the singleton was purely automatic, its timing should not have been affected by a Go/No-Go decision whether to perform the search or not.
To determine if inter-trial priming changes in the low-level sensory features, i.e., the colour of the display items, influenced the timing of attentional selection in Experiment 5, the N2pc latency on Colour-Repeat trials was compared with the N2pc
latency on Colour-Change trials. The salience-driven selection theory would predict that the N2pc should occur earlier on Colour-Repeat trials. This is because on Colour-Repeat trials the observers searched for a singleton with the same sensory features as the singleton they searched for on the preceding trial and, thus, the effective salience of the pop-out item should presumably increase via bottom-up priming. The results were not consistent with this prediction, however. The fractional peak latency of the N2pc on Colour-Repeat trials (215 ms) was not significantly different from that of the N2pc on Colour-Change trials (221 ms; see Figure 16), t < 1. This result indicates that inter-trial changes in the bottom-up, sensory features of the display items did not affect the timing of attentional selection of the singleton.

![Figure 16](image.png)

**Figure 16.** Contralateral-ipsilateral difference waveforms recorded at electrodes PO7/8 for Colour-Repeat and Colour-Change trials in Experiment 5. The arrows indicate the 70% fractional peak latency of the N2pc.

To examine the effect of inter-trial changes in a low-level sensory feature (colour) of the display items on the magnitude of the N2pc, the mean amplitude of the N2pc on Colour-Repeat trials in the 235-265 ms time window (-0.77 µV) was compared with the mean amplitude of the N2pc on Colour-Change trials in the same time window (-0.56 µV). The difference between the N2pc amplitudes was not significant, \( F(1,17) = 2.62, MSe = .14, p = .12, \eta^2_p = .13 \).
Although the target N2pc in Experiment 4 appeared to be larger and earlier on Colour-Repeat trials than on Colour-Change trials, neither the amplitude difference nor the latency difference between the two subsets of trials was significant. Moreover, the finding that the amplitude difference was not significant rules out the possibility that the amplitude difference may have complicated interpretation of the apparent earlier onset of the N2pc on Colour-Repeat trials (cf. Luck, 2005). Additionally, measuring the onset latency as fractional peak latency (time at which the N2pc reached 70% of its peak amplitude) factored out any amplitude difference. The finding that inter-trial changes in colour of the display items did not affect the latency or the amplitude of the N2pc elicited by the pop-out item argues against the effect of selection history at the low level of sensory features on attentional selection in pop-out search.

3.4. Discussion

Experiments 4 and 5 investigated the roles of goal-driven and stimulus-driven factors in attentional selection in pop-out search. Six main ERP results were obtained from the two experiments and the comparison between their results: (i) The pop-out item in Experiment 4 elicited an N2pc when the search display was task-relevant (Go trials), but no N2pc was in evidence when the search display was task-irrelevant (No-Go trials); (ii) The target N2pc occurred later when the observers were required to make the Go/No-Go decision (Experiment 4) compared to when such decision was not required (Experiment 5); (iii) The target N2pc in Experiment 4 occurred earlier on Go-Repeat trials than on Go-Change trials; (iv) The ERP indices of the Go/No-Go decision in Experiment 4 (divergence of the N2b and the P2a waves on Go and No-Go trials) occurred noticeably earlier than the target N2pc; (v) An ERP index of response inhibition (the No-Go P3) was obtained on No-Go trials in Experiment 4; (vi) The target N2pc in Experiment 5 occurred at approximately the same latency on Colour-Repeat and Colour-Change trials.

Three findings indicate that the Go/No-Go decision was made before an observer deployed attention to the singleton: (1) the pop-out item elicited an N2pc only when the search display was task-relevant; (2) the N2b and the P2a waves diverged on Go and No-Go trials substantially earlier than the onset of the target N2pc on Go trials; and (3)
the Go/No-Go decision delayed the onset of the N2pc compared to when such decision was not required. This pattern of results is inconsistent with the salience-driven selection theory, unless one subscribes to the notion of attentional window, discussed below.

Attentional window is defined as the region in the visual display to which an observer attends at any given moment (Theeuwes, 1994a, 2004). According to the salience-driven selection theory, the location and the size of attentional window is under top-down control and is the only area in the search display within which preattentive analyses of salience are performed (Theeuwes, 2010). From this perspective, if the observers’ attentional window in Experiment 4 was narrowed in order to scrutinize the colour of a single item in the display, the pop-out item would fall outside the attentional window, and, therefore, its salience would not be computed preattentively. This option does not appear to be likely to occur in Experiment 4, however. This is because it is known that observers can select a group of items when the task requires no item individuation (Mazza et al., 2007). Since the current Go/No-Go decision could be made based on the colour of all the items in the display, it is likely that the entire array of items was selected. Thus, the Go/No-Go decision was unlikely to involve spatial selection of an individual item and, therefore, would not result in a narrow attentional window. The role of attentional window in visual search will be further investigated in Chapter 4.

The difference in the N2pc latency between Go-Repeat trials and Go-Change trials in Experiment 4 (51 ms) was comparable to two other costs: (i) the behavioural cost of the Go/No-Go decision (53 ms) as measured by the difference between the RT on Go trials in Experiment 4 and on All-Go trials in Experiment 5; (ii) the attentional cost of the Go/No-Go decision (62 ms) as measured by the difference between the N2pc latency on Go trials in Experiment 4 and on All-Go trials in Experiment 5. The finding that the effect of inter-trial changes in the Go status of trials was comparable to the total behavioural and attentional costs of the Go/No-Go decision points to the important role of selection history at the level of observer’s goals in the control of attentional selection in visual search.

The noticeable effect of inter-trial Go/No-Go changes on the latency of the N2pc indicates that the speed with which the Go/No-Go decision could be made was influenced by the task set: that is, if the observers had been presented with a No-Go
display on the preceding trial, it would take them longer to deploy their attention when faced with a Go display on the present trial. This is presumably because, under those circumstances, the observers would have to overcome the lingering inhibitory effect stemming from the preceding No-Go trial. This interpretation is consistent with the occurrence of the No-Go P3 activity originating from the ACC that is known to be involved in response inhibition and control.

More generally, these results represent an example of situations in which caution should be exercised so as to avoid conflating ‘top-down’ and goal-driven control of attention. Had the inter-trial Go/No-Go changes in the observer’s current goals not been examined, it might have been tempting to attribute the attentional cost of the Go/No-Go decision to a purely top-down (volitional) control of attention. In fact, inter-trial changes in the observer’s goals, but not in the sensory features of the stimuli, were found to influence the timing of attentional selection. This pattern of results argues in favour of the integrated-priority model (Awh et al., 2012), in which the observer’s previous goals – but not necessarily the previous sensory features of the stimuli – influence the attentional selection in the present.
Chapter 4.

The role of attentional window in salience-driven selection

4.1. Introduction

A tenet of the salience-driven selection theory is that salient singletons capture attention automatically. Early evidence in support of this theory was obtained with *abrupt visual onsets*, which are highly salient and provide a strong, bottom-up signal to vie for attention (Yantis & Jonides, 1984; for a review, see Egeth & Yantis, 1997). Early studies suggested that abrupt onsets captured attention automatically, but subsequent studies showed that abrupt onsets do not always capture attention in violation of an observer's intention. Specifically, capture can be prevented when attention is voluntarily engaged at a specific location (Yantis & Jonides, 1990; Theeuwes, 1991). Moreover, singletons in a feature dimension that varies over space but not time (*static singletons*) do not capture attention automatically (Folk et al., 1992; Jonides & Yantis, 1988; Yantis, 1993; Yantis & Egeth, 1999).

To account for these inconsistencies, Belopolsky et al., (2007) adopted the notion of spatial “attentional window”, defined as the region in the visual display to which an observer attends (Theeuwes, 1994a, 2004). Belopolsky et al. employed the paradigm originally developed by Jonides and Yantis (1988), in which observers searched serially for a target letter that occasionally had a unique colour. The factor used to manipulate the observer’s attentional window was the search-task condition: the observers were asked to search for either a local shape in the center of the display (*focused-attention condition*) or a global shape (*diffuse-attention condition*). Based on behavioural results, the colour singleton in the focused-attention condition did not appear to capture attention. In contrast, the colour singleton in the diffuse-attention condition did appear to
capture attention, as evidenced by more efficient search when the color singleton itself was the target (see also Folk & Annett, 1994; Franconeri & Simons, 2003). Belopolsky et al. interpreted these results to indicate that when an observer’s attentional window is wide enough to contain a salient item, attention is captured automatically to the location of that item. In contrast, salient items that fall outside the observer’s attentional window are presumed not to capture attention because pre-attentive analyses are performed only within the attentional window (see also Hernández, Costa, & Humphreys, 2010).

Belopolsky & Theeuwes (2010) employed the notion of attentional window to address the controversy regarding the necessity of attentional involvement in pop-out search (e.g., Braun & Sagi, 1990; Luck & Ford, 1998; Müller et al., 2003; Reddy, Moradi, & Koch, 2007; Treisman, 1988) that included several studies suggesting that attention is necessary to search for a pop-out item (Joseph, Chun, & Nakayama, 1997; Nothdurft, 1999; Theeuwes, 1992; Theeuwes, Kramer, & Atchley, 1999; Theeuwes et al., 2008). Belopolsky and Theeuwes hypothesized that if attention is required to search for a pop-out item, then narrowing of the observer’s attentional window should have two consequences: (i) capture of attention by an irrelevant pop-out item should be avoided, because the pop-out item will fall outside the attentional window; (ii) the efficiency of a pop-out search should decrease. This is because it is presumed that, with a narrow attentional window, preattentive search for salient items cannot be performed in parallel across the visual display, and, therefore, visual search becomes more serial.

Belopolsky and Theeuwes’ (2010) results were consistent with predictions from the attentional-window hypothesis (Belopolsky et al., 2007; Theeuwes, 1994a, 2004). Namely, when the observers’ attentional window was diffuse, the presence of a colour-singleton distractor slowed search for a shape-singleton target (see Theeuwes, 1992). In contrast, when the observers’ attentional window was narrow, the colour-singleton distractor did not interfere with target search. Moreover, Belopolsky and Theeuwes found that in a focused-attention condition, search for a pop-out item became less efficient, indicating that visual search had become more serial.

Based on the results from these studies on attentional window, the salience-driven selection theory postulates that there is a role for ‘top-down’ or goal-driven control in initial attentional selection, but it is mainly limited to varying the size of the attentional
window. Upon selection of an attentional window, preattentive salience computations are said to occur automatically within that window. These preattentive computations are presumed to give rise to automatic spatial selection of the most salient item within the attentional window (Theeuwes, 2010). In other words, it is hypothesized that the most salient item within the observer’s attentional window always captures attention automatically.

To assess this hypothesis, it was required to design a visual-search task that employed identical stimuli in two different conditions: one in which a target singleton is located within the observer’s attentional window, and another in which an irrelevant singleton falls within the attentional window. If, according to salience-driven selection theory, the most salient item within the attentional window captures attention automatically, there should be ERP evidence of attentional selection, regardless of whether that singleton is relevant to the observer’s current goals or not. In contrast, if the goal-driven control can avoid capture of attention by an irrelevant singleton within the attentional window, ERP evidence of attentional selection should be obtained only when the singleton is relevant to the task at hand.

To test these predictions, a visual-search task was designed in Experiment 6 in which the display consisted of a single, red salient bar and a circular disk-shaped dark-grey area defined by subtle luminance contrast against a light-grey background. In the target-disk condition, the observers were explicitly asked to spread their attention over the entire surface of the disk in order to discriminate the size of the disk. Both the large and the small disk always contained the salient bar. In this condition, the attentional window was presumed to be wide enough so as to allow the observers to discriminate the size of the disk. In the target-bar condition, which always followed the target-disk condition with identical stimuli, the disk was irrelevant, and the observers discriminated the length of the bar regardless of the size of the disk. In this condition, the attentional window was presumed to narrow so as to focus attention on the salient bar. Thus, while the salient bar was task-irrelevant in the target-disk condition and task-relevant in the target-bar condition, it was always located within the observer’s attentional window in both conditions.
The salience-driven selection theory (and the attentional-window hypothesis) would predict that since the salient bar was located within the observer's attentional window in both target-disk and target-bar conditions, we should obtain an N2pc in both cases. From the perspective of goal-driven control, however, the salient bar should elicit an N2pc only in the target-bar condition, i.e., when the salient item was relevant to the observer's current goal. The ERLs would also allow observing any ERP trace of spatial selection of the salient item in the pre-N2pc time range.

4.2. Experiment 6

4.2.1. Methods

Participants

12 participants were drawn from the same population as Experiments 1 to 5. None had participated in previous experiments. Data from 2 participants were excluded from analyses because of excessive blinks or eye movements. Each of the remaining 10 participants (8 women, age 20.0 ± 2.4 years, mean ± SD) reported normal or corrected-to-normal visual acuity and had normal colour vision.

Apparatus

This was the same as in previous experiments.

Stimuli and Procedure

All stimuli were presented on a grey background (RGB = 120, 120, 120). Search displays consisted of either a large (19° diameter) or a small (18° diameter) grey disk (RGB = 125, 125, 125) at the center of the screen. On each trial, either a long (1.7° x 0.4°) or a short (1.4° x 0.4°) red horizontal bar was presented randomly at one of 12 possible locations on an imaginary circle (14.2° diameter) at the center of the screen, with three equidistant locations per quadrant. The imaginary line connecting the center of the red bar to the center of the screen yielded 10°, 30°, or 50° in the top right quadrant, 130°, 150°, or 170° in the bottom right quadrant, 190°, 210°, or 230° in the bottom left quadrant, and 310°, 330°, or 350° in the top left quadrant, relative to the
vertical meridian. Since the eccentricity of the red bar (7.1°) was smaller than that of the small grey disk (9°), the red bar was always located within either the small or the large grey disk. Examples of search displays used in Experiment 6 are illustrated in Figure 17.

Figure 17. **ERPs recorded at electrodes PO7/8** in Experiment 6. The top and bottom panels illustrate the ERPs obtained in the Target-Disk and Target-Bar conditions, respectively. The top display illustrates a long bar inside a large disk, whereas the bottom display illustrates a short bar inside a small disk.

At the beginning of each experimental session, the participants were asked to match the brightness of a red rectangle to a grey rectangle with the same RGB values as the grey disk. This procedure was similar to that mentioned in the Methods section of Experiment 1. The R-value for the red rectangle obtained in the brightness-matching procedure was used to present the red bar during the experiment. Each trial began with
a fixation display for 400–800 ms followed by a search display that remained on screen for 750 ms. The fixation display contained a white fixation dot on a grey background. The search display contained the red line and a faint light-grey disk on the grey background. An experimental session consisted of two conditions with identical stimuli. In the first condition (Target-Disk condition), participants were explicitly instructed to spread their attention over the entire area of the disk and to discriminate the size of the disk by pressing one of two mouse buttons, while the bar was task-irrelevant. In the second condition (Target-Bar condition), participants discriminated the length of the bar by pressing one of two mouse buttons, while the disk was task-irrelevant. The Target-Disk condition was always presented first, so that participants would not assign ‘target’ attributes to the red bar while they performed in the Target-Disk condition. In both conditions, the trials with small and large disks as well as short and long bars were randomly intermixed.

In the Target-Disk condition, participants were required to perform a size-discrimination task based on the diameter of the disk. Therefore, it is plausible that the proposed attentional window corresponded roughly to the area covered by the grey disk. In the Target-Bar condition, however, participants were required to attend to the specific location of the red bar and perform a length-discrimination task. Since the red bar was always presented at a fixed eccentricity, the attentional window corresponded roughly to the imaginary circle defined by the possible locations of the red bar. Thus, it could be argued that in both Target-Disk and Target-Bar conditions, the red bar was always located within the attentional window.

Each experimental block consisted of 48 trials, and each participant completed 15 experimental blocks, for a total of 720 experimental trials, after performing a practice block. Participants were allowed to take a short break after each block.

**Electrophysiological Recording and Data Analyses**

These were the same as in previous experiments except for the following changes. ERPs were averaged separately for Target-Disk and Target-Bar conditions. The N2pc, Ppc, and SPCN waveforms were measured in the 175–225 ms, 107–137 ms, and 400–800 ms time windows, respectively.
4.2.2. Results and Discussion

Behaviour

The mean accuracy was 96.9\% and 91.1\% for the Target-Disk and the Target-Bar conditions, respectively. The difference between the two accuracies was significant, $t(9) = 5.94$, $p < .001$. The median RT was 490 ms and 556 ms for the Target-Disk and the Target-Bar conditions, respectively. The difference between the two reaction times was also significant, $t(9) = 5.05$, $p = .001$. Since observers were both faster and more accurate in the Target-Disk condition, there was no speed-accuracy tradeoff between the two conditions.

Electrophysiology

Figure 17 displays the grand-averaged ERPs recorded contralateral and ipsilateral to the red bar, separately for the Target-Disk and Target-Bar conditions. Figure 18 displays the contralateral-ipsilateral difference waveform for the two conditions. All of these ERPs were recorded over the occipital scalp (electrodes PO7/8).

N2pc

An ANOVA was performed on the mean ERP amplitude in the N2pc time window with Electrode Lateralization (contralateral vs. ipsilateral) and Condition (Target-Disk vs. Target-Bar) as within-subject factors. The main effect of Electrode Lateralization was significant, $F(1,9) = 32.21$, MSe = .42, $p < .001$, $\eta^2_p = .78$, whereas the main effect of Condition showed a trend toward significance, $F(1,9) = 3.77$, MSe = .62, $p = .08$, $\eta^2_p = .30$. Critically, the interaction was significant, $F(1,9) = 47.99$, MSe = .26, $p < .001$, $\eta^2_p = .84$. Subsequent analyses confirmed that the N2pc in the Target-Bar condition (-2.28 µV) was statistically significant, $t(9) = 6.71$, $p < .001$, whereas the N2pc in the Target-Disk condition (-0.05 µV) was not significant, $t < 1$. 
Figure 18. Contralateral-ipsilateral difference waveforms recorded at electrodes PO7/8 for Target-Disk and Target-Bar conditions in Experiment 6.

The finding that the singleton elicited an N2pc in the Target-Bar condition but not in the Target-Disk condition indicates that attentional filtering did not occur at the location of the most (and the only) salient item in the display when that item was irrelevant to the observer’s current goals. This pattern of results indicates that salient objects within the observer’s attentional window do not necessarily capture attention, and that there is goal-driven control over selection even within the attentional window.

Ppc

Similar to the N2pc analysis, an ANOVA was performed on the mean ERP amplitude in the Ppc time window with Electrode Lateralization (contralateral vs. ipsilateral) and Condition (Target-Disk vs. Target-Bar) as within-subject factors. The main effect of Electrode Lateralization was significant, $F(1,9) = 38.18$, MSe = .19, $p < .001$, $\eta^2_p = .81$, whereas the main effect of Condition showed a trend toward significance, $F(1,9) = 4.20$, MSe = 1.52, $p = .07$, $\eta^2_p = .32$. The interaction effect was not significant, $F < 1$. The absence of an interaction indicates that the Ppc amplitudes were comparable in the two conditions. Subsequent analyses confirmed that both the Ppc in the Target-Bar condition (0.91 $\mu$V), $t(9) = 6.07$, $p < .001$, and the Ppc in the Target-Disk condition (0.80 $\mu$V), $t(9) = 4.64$, $p = .001$, were significant.
The singleton elicited a Ppc in both Target-Disk and Target-Bar conditions, and there was no significant difference in the Ppc amplitude between the two conditions. Importantly, the singleton Ppc in the Target-Disk condition was not followed by a singleton N2pc. On the face of it, the Ppc elicited in both conditions might be regarded as evidence for the early spatial selection of a salient singleton that results in automatic capture of attention proposed by the salience-driven selection perspective. However, when considered together with the Ppc results obtained in Experiments 1 to 3, it can be concluded that: (i) the Ppc tracks the location of the salient visual stimulus regardless of its task-relevance; (ii) the presence of Ppc does not reliably predict capture of attention by a salient item, even when that salient item is located within the observer’s attentional window; (iii) the Ppc does not predict interference with the attentional selection of the target (in the additional-singleton paradigm employed in Experiments 1 to 3).

**SPCN**

Similar to the N2pc and the Ppc analyses, an ANOVA was performed on the mean ERP amplitude in the SPCN time window with Electrode Lateralization (contralateral vs. ipsilateral) and Condition (Target-Disk vs. Target-Bar) as within-subject factors. The main effect of Condition was significant, \( F(1,9) = 16.62, \text{MSe} = 1.70, p = .003, \eta^2_p = .65 \), whereas the main effect of Electrode Lateralization showed a trend toward significance, \( F(1,9) = 3.13, \text{MSe} = .34, p = .11, \eta^2_p = .26 \). Critically, the interaction was significant, \( F(1,9) = 19.99, \text{MSe} = .11, p = .002, \eta^2_p = .69 \). Subsequent analyses confirmed that the SPCN in the Target-Bar condition (-0.79 µV) was significant, \( t(9) = 3.01, p = .015 \), whereas the SPCN in the Target-Disk condition (0.13 µV) was not significant, \( t < 1 \).

The singleton in the Target-Disk condition did not elicit either an N2pc or an SPCN. These two findings indicate that although the task-irrelevant singleton was the only salient item within the observer’s attentional window, it was not able to access VSTM because it was not attentionally selected for further processing.
Chapter 5.

General Discussion

The issue of whether salient singletons capture attention automatically has been contentious for over 20 years. According to the salience-driven selection perspective, the location of the most salient item in the display is detected preattentively, after which attention is deployed automatically to that location. By this account, the presence of a salient distractor delays search for a less-salient target because attention is deployed initially to the distractor location and then to the target location only after the distractor has been identified and dismissed (Theeuwes, 2010). By other accounts, the presence of a salient distractor delays search because the system must first determine to which of the two singletons attention should be deployed before deploying attention directly to the target location (i.e., nonspatial filtering costs; Folk & Remington, 1998, 2006).

The present series of experiments were designed to examine the ERP evidence for the salience-driven selection theory and other theories of visual search using additional-singleton, pop-out search, and attentional-window paradigms. In Experiments 1 to 3, search displays with one lateral singleton and one midline singleton were used to isolate the target and distractor ERLs. A main question was whether a salient distractor would elicit the N2pc because that component has been linked to attentional selection. Such a finding, in association with salience-driven RT interference, would provide clear evidence for the salience-driven selection hypothesis. This was not the case, however. In Experiment 1, the salient-but-irrelevant colour singleton did not elicit an N2pc, even on slow-response trials. Based on this result, it can be concluded that attentional filtering did not occur at the distractor location. This conclusion is not based solely on a null result, i.e., the absence of a distractor N2pc, but rather on a clear pattern of ERP results. Specifically, when search displays contained a target singleton and a distractor singleton, it was the target – not the distractor – that elicited the N2pc. In other words,
when the salient distractor was pitted against a less-salient target, observers attended to the target rather than the distractor.

In Experiment 3, there was a relatively large distractor-interference effect. According to the salience-driven selection theory, this large effect reflects an increased attentional dwell time at the distractor location, and therefore, should have resulted in a distractor N2pc (Theeuwes, 2010). The finding that no distractor N2pc was in evidence for all-trials ERPs indicates that attention capture did not occur on a majority of trials. The salient colour singleton did elicit an N2pc on slow-response trials. This indicates that the distractor singleton occasionally captured attention before observers could redeploy their attention to the target location.

The N2pc results of Experiments 1 and 3 should be considered in combination with the N2pc results obtained with a mixed-feature variant of the additional-singleton paradigm (McDonald et al., 2013), and in light of the critical differences in the design of the three experiments. In McDonald et al.’s study, both the colour and the shape of the two singletons would occasionally swap throughout the experiment. In other words, the colour or the shape of the distractor singleton on any given trial could be the same as the colour or the shape of the target on one of the preceding trials. In contrast, there was no swapping of features (either colour or shape) between the two singletons throughout the Experiment 1. That is, neither the colour nor the shape of the distractor on a given trial was ever the same as the colour or the shape of the target on any preceding trial. Besides having a highly variable and, thus, unpredictable distractor, Experiment 3 had important differences with both mixed- and fixed-feature search paradigms: the colours of the two singletons (which was the defining feature of the distractor singleton) never swapped, but their shapes did. The finding that the distractor elicited an N2pc only on slow-response trials in both Experiment 3 and McDonald et al.’s study, but not in Experiment 1, indicates that observers occasionally attend to the salient distractor, if target and distractor swap their features in the dimension in which the target singleton is defined.

The N2pc results of Experiments 4 to 6 were consistent with the above view. In Experiments 4 and 5, an orientation singleton did not elicit an N2pc when it was irrelevant to the observer’s current goals, even though it was the most salient item in the
display. In Experiment 6, the only singleton within the observer’s attentional window failed to elicit an N2pc when it was task-irrelevant. This finding indicates that goal-driven control over bottom-up salience can extend to the items located within the observer’s attentional window.

One important finding in Experiment 1 was the presence of P_D on fast-response trials, but not on slow-response trials. This is consistent with the hypothesis that distractor suppression led to more efficient search but could not be implemented on all trials. Since the features of target and distractor do not vary in a fixed-feature search, one could ask what underlies this trial-to-trial variability. One factor may have been the intermittent and unpredictable presence of the distractor. According to Müller and colleagues (2003), participants are better able to deal with potentially distracting stimuli when those stimuli occur regularly. By this account, participants in Experiment 1 may have been better able to suppress the distractor when the distractor was present on the preceding trial(s). A second potential factor may have been the random fluctuation of top-down control settings. Consistent with this option, Leber (2008) reported a negative correlation between the strength of the pre-trial fMRI signal in middle frontal gyrus (MFG) and the magnitude of distractor interference. Such trial-by-trial fluctuations in the strength of top-down control can also occur in fixed-feature search, although perhaps to a less extent compared to mixed-feature search. Namely, on trials with high pretrial MFG activity, it might have been more likely to observe a P_D and small distractor-interference effect, whereas on trials with low pretrial MFG activity, it might have been more likely to observe no P_D and a large distractor-interference effect.

In Experiment 2, a P_D was observed in all-trials ERPs. This indicates that when the features of target and distractor singletons were held constant, and the distractor was less salient than the target, the observers were able to suppress the distractor location on most trials. In Experiment 3, however, no P_D was observed even on the trials with the fastest response. This indicates that it is quite difficult for observers to suppress a more-salient and highly unpredictable distractor. This inability to suppress presumably underlied the occasional capture of attention to the distractor location on slow-response trials.
Recently, there has been debate about whether the absence of an N2pc to a salient distractor rules out salience-driven attention capture. According to Theeuwes (2010), attention can be deployed to the distractor location and then redeployed to the target location without eliciting a distractor N2pc. This fleeting-capture account is based on the view that the N2pc does not reflect the initial selection of an object but rather some enduring attentional process that follows. According to Eimer and Kiss (2010), however, the absence of a distractor N2pc would indicate that attention was never deployed to the distractor location. This claim is based on the view that the N2pc does reflect initial object selection. In the present work, N2pc shares attributes with both of these contrasting views. Like Theeuwes, the possibility is left open for an initial spatial selection prior to the attentional process that gives rise to the N2pc (see Fig. 1). However, like Eimer and Kiss, the present work considers the N2pc to reflect an early stage of object selection – namely, the initial selection of an object via an ambiguity-resolution process labeled filtering in Figure 1 (cf. Hickey et al., 2009; Hopf et al., 2002; Luck et al., 1997; Luck & Hillyard, 1994b).

Although it is possible that spatial selection precedes the attentional process that gives rise to the N2pc, as suggested by Theeuwes (2010), such fleeting capture is not considered to be plausible at this point. The crux of the matter is whether an attended item can be identified and dismissed without eliciting an N2pc. The fleeting-capture account is contingent on the assumption that it can. In contrast, it can be argued that in visual search (i) identification is possible only after attentional filtering has resolved the neural ambiguities arising from the presence of multiple, dissimilar items (cf. LaBerge & Brown, 1989); (ii) attentional filtering gives rise to the N2pc. Based on these premises, it can be concluded that identification of one item appearing among other dissimilar items is possible only after the N2pc has occurred (see Fig. 1). Thus, if participants had attended and identified the salient distractor before redeploying attention to the target, a distractor N2pc should have been in evidence on most trials.

In addition to these theoretical considerations, three empirical results obtained in the current study also argue against fleeting capture by the salient distractor. First, in Experiment 1, the distractor not only failed to elicit the N2pc but also elicited a P0 on fast-response trials. On the grounds that the P0 reflects attentional suppression (Hickey et al., 2009), this indicates that on fast-response trials, observers suppressed the
location of the distractor to prevent that item from capturing attention (see also Sawaki & Luck, 2010). One might assume alternatively that observers would need to select and identify the distractor in order to suppress it. Such a processing sequence would likely entail an N2pc (signifying object selection) prior to the P_D (signifying suppression). In fact, a similar sequence of target-elicited ERLs has been reported (Sawaki, et al., 2012): the target N2pc associated with selection was followed by a P_T, which was interpreted as termination of target processing via suppression. The finding that the salient distractor in Experiment 1 elicited a P_D but no preceding N2pc indicates that the suppression was applied on the basis of the preattentive analysis alone. Specifically, in Experiment 1, the preattentive stage of processing would culminate in the construction of a salience map on which the distractor location is determined to have the highest salience (without identifying the features at that location). The visual system could selectively suppress the location of the most salient item on the map in order to prevent selection and identification of the item at that location. This would enable selection of the less salient target without first selecting the distractor. The finding that no P_D was in evidence in Experiment 3 indicates that such suppression is critically dependent on the predictability of the distractor. If the salient distractor is highly unpredictable, the observers may not be able to suppress it on most trials.

Second, if the salient distractor in Experiment 1 captured attention, even briefly, the RT-interference effect should have been larger in Experiment 1 than in Experiment 2. This was not the case: the overall interference effects were equal in the two experiments. Whereas the interference effect appeared to be smaller than that reported by Theeuwes (1992), it was on par with interference effects observed in recent fixed-feature search tasks (e.g., Schübo, 2009; Töllner, Müller, & Zehetleitner, 2012).

Third, neither the presence nor the relative location of the salient distractor in Experiment 1 affected the latency or the amplitude of target N2pc. Because it is unlikely that attention was deployed to the distractor location, disengaged, and then redeployed to the target location without affecting the target N2pc in any way, this pattern of results is inconsistent with the fleeting-capture variant of the salience-driven selection hypothesis. The relative location of the salient distractor in Experiment 3 did affect the amplitude of target N2pc, but in the opposite direction of what would be expected from the salience-driven selection theory. The target N2pc was smaller for ipsilateral-
distractor than for contralateral-distractor trials. If attention was deployed to the distractor location first, the target N2pc should have been smaller for contralateral-distractor displays, in which the distractor was, on average, more distant from the target compared to ipsilateral-distractor displays.

Stimulus salience was found to influence the ERPs obtained in Experiments 1 and 2 in two ways. First, the target N2pc was earlier (and larger) when participants searched for the colour singleton (Experiment 2) rather than the shape singleton (Experiment 1). This latency effect was in evidence even on distractor-absent trials, indicating that the effect was driven by target salience, not distractor salience. A similar, albeit larger, difference was observed for mean RTs, which were shorter in Experiment 2 than in Experiment 1. Thus, the N2pc latency effect is in line with the existing behavioural evidence that increasing target salience (e.g., by increasing target-distractor dissimilarity) leads to faster search (Duncan & Humphreys, 1989; Nagy & Sanchez, 1990; for review, see Wolfe & Horowitz, 2004).

Second, the salient colour singleton elicited a Ppc both when it was a distractor (Experiments 1, 3, and 6) or the target (Experiments 2). The latter finding rules out the possibility that the Ppc reflects suppression of an attend-to-me signal (Sawaki & Luck, 2010). It is possible that the Ppc reflects the initial spatial selection of the salient colour singleton. As noted above, however, the presence of the distractor in Experiment 1 had no influence on the target N2pc. Thus, if the Ppc reflected the initial spatial selection of the colour singleton, such selection had no impact on target processing in Experiment 1. Moreover, the distractor Ppc elicited by the Tm/Dl display on slow-response trials was followed by a distractor N2pc in Experiment 3, but not in Experiment 1. Similarly, the singleton Ppc in Experiment 6 was followed by a singleton N2pc in the Target-Bar condition, but not in the Target-Disk condition. These results indicate that eliciting a Ppc by a salient singleton does not predict or prevent initial capture of attention by that distractor. The Ppc might alternatively be linked to laterally imbalanced sensory activity (Luck & Hillyard, 1994a) or representation of salient items on a salience map (Fortier-Gauthier et al., 2012).

On the basis of the present results, the sequence of hypothetical processing steps illustrated in Figure 19 is proposed to take place in many visual search tasks. As
was noted in the context of the salience-driven selection hypothesis (see Fig 1), the entire visual display is processed in parallel at the earliest preattentive stage. This culminates in a salience map on which the locations of the two most salient singletons (if present) are represented. This process is placed in an intermediate stage rather than the earliest stage of preattentive processing on the evidence that the visual system monitors a limited number of high-priority locations for purposes of assigning priority for attentional selection (e.g., Yantis & Johnson, 1990). Whereas the salience-driven selection hypothesis asserts that information at the location of the most salient item is passed to the attentive stage automatically, the present work proposes that the visual system can selectively use the contents of the salience map in two different ways. One way is analogous to the conventional notion of selection, herein called selection for identification. Additionally, the visual system can suppress the locations of salient items so that those items do not gain access to the selection-for-identification pathway. The present work proposes that when a predictable distractor singleton is more salient than the target, the location of the most salient item is suppressed to enable more efficient selection of the target. This suppression, indexed by the PD, takes effort and is applied at the earliest stage possible (ideally by the time filtering begins at the target location). However, if the more-salient distractor is highly unpredictable, the visual system may have difficulty suppressing its location. This failure to suppress the distractor can result in occasional capture of attention.

The framework outlined above has similarities to the signal suppression hypothesis of controlled attention capture, which was introduced by Sawaki and Luck (2010) to account for what appeared to be a PD (but occurred in the Ppc time range) contralateral to a salient-but-irrelevant colour singleton. According to Sawaki and Luck, the most salient item generates an “attend-to-me” signal that can be suppressed when the features of the eliciting item do not match the current attentional control settings. In the context of the salient-signal suppression view proposed in the present work, this “attend-to-me” signal is likely associated with activation on the salience map. Here, it should be emphasized that multiple items are represented on the salience map and that each of these items – not just the most salient item – generate “attend-to-me” signals (Jannati, Gaspar, & McDonald, 2013).
The effects of goal-driven attentional control are not limited to suppressing the location of a salient distractor. Experiments 4 and 5 showed that the visual system is able to halt the progression of processing sequence into the attentive stage until a decision to perform visual search is made. If such a decision is not made, the perceptual-filtering stages will not ensue. Those two experiments also revealed that selection history, at the level of observer’s goals, can influence the timing of entry into the attentive stage in the present. Finally, Experiment 6 showed that even when a singleton is the most salient item within the observer’s attentional window, it may generate a spatial, “attend-to-me” signal, but that signal will not necessarily be followed up on by the attentive stage if the singleton is not relevant to observer’s current goals.
References


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