

Perceptual Salience and Its Consequences on Attentional Object Selection

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Abstract

This thesis investigated the effects of salience on visual object selection, and focused on whether salience impacts the visual system's ability to process multiple items at the same time (parallel selection) or one-at-a-time (serial selection). Chapter 2 consists of two experiments that used an ERP component, the N2pc, to track the deployment of attention in a visual search task with highly dissimilar distractors. Although the time to find the target increased with the number of distractors, observers were able to select the target at the same time, regardless of the size of the search display. This suggests that task relevance can make otherwise non-salient items "pop out" at the level of attentional selection. Chapter 3 comprises a single experiment in which attentional selection was measured overtly, using eye tracking, as observers inspected and compared two singletons of differing salience. Discreet eye movements were made from one singleton to the other and the order of inspection was strongly biased by target salience, with the initial saccade being made to the more salient singleton on the vast majority of trials. This suggests that, in the absence of top-down control, the order of attentional selection is dictated by salience. Finally, Chapter 4 consists of three variants of the same two-singleton search task used in Chapter 3. The first experiment replicated Chapter 3 but with attentional selection tracked covertly via the N2pc. In the next two experiments, task parameters were manipulated to encourage slower shifts of attention from one singleton to the other and to encourage the initial inspection of the less salient singleton. Attentional object selection was purely serial in some cases and partially parallel in others. The biasing effect of salience could also be subverted, such that the less salient item was selected first, however that item was not selected as rapidly as the more salient item. Chapter 4 thus reveals that (i) the earliest time at which an item becomes available for attentional selection depends on its relative salience, and (ii) the speed of attentional redeployment varies with the nature of the response required.

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Chapter 1. Introduction

All mammals use information obtained from the surrounding environment to guide behavior, promote survival, and reproduce. In humans, our phenomenological experiences of the world around us, and the declarative knowledge we possess of it, have been imparted to us from information perceived by the senses. For psychologists attempting to understand and predict human behavior, an important goal has been to understand how the mind and brain process and ultimately act upon this stream of sensory information. Early theories considered organismal responses, including complex human responses, as the inevitable consequence of stimulus processing. However, it quickly became apparent that complex behavior could not be adequately explained by the straightforward mapping of stimulus to response. For example, if an organism is presented with two sources of information that indicate two different, mutually incompatible responses, what response—if any—is made? Likewise, if reward is received following a response made to the presentation of two stimuli, to which stimulus is that reward mapped?

These kinds of ambiguous situations cannot be resolved without a mechanism that can prioritize certain information—certain stimuli—over others. In contemporary usage, this ability is called *selective attention* (Desimone & Duncan, 1995; LaBerge, 1995). In his seminal definition, the American psychologist William James described attention as “taking possession ... of one out of what seems several simultaneously possible objects” (James, 1890). Many years later, cognitive psychologists would test this theory of constrained awareness in controlled settings. This was elegantly demonstrated in a pair of early studies by Donald Broadbent. In the first, participants were shown a test array that was divided into numbered segments, with simple shapes contained within some of these regions (Broadbent, 1952a). Via a loudspeaker, participants were asked a series of simple yes-or-no questions, such as “is there a cross in segment four?” Participants had no trouble answering these questions if they were presented one at a time, but they had great difficulty responding if several questions were asked

simultaneously. This highlights the first of two fundamental aspects of information processing: the mind can apprehend a limited amount of sensory input at any given time. In the subsequent experiment, overlapping instructions were again provided, but this time from a pair of loudspeakers (Broadbent, 1952b). Participants again struggled to respond to instructions, but were able to answer much more easily after they were told to obey instructions from one speaker and not the other. This highlights the other fundamental aspect of information processing: the mind can overcome capacity limitations by selecting a subset of the available sensory information for processing.

Today, there is overwhelming evidence that the subset of information that is selected is biased by two complementary control mechanisms. The first selects information based on conspicuousness. At various points we have all had the experience that our attention was captured seemingly automatically by a loud noise, a sudden movement or a brightly colored object. Accordingly, this process is often called salience-driven selection. Typically, a stimulus is considered salient when there are marked differences between it and its surrounding stimuli (Allman, Miezin, & McGuinness, 1985; Desimone, Schein, Moran, & Ungerleider, 1985). A red circle is perceived as being more salient if it is surrounded by green circles than if it is surrounded by orange ones. The second process directs attention volitionally towards items of interest, including non-salient ones. This process is under a person's voluntary control, and is often called goal-driven selection.

In the laboratory, countless numbers of experiments have been devised to study the processes mediating selective attention within the domain of vision. In broad terms, many of these experiments can be sorted into three categories. The first is the cueing paradigm, which was devised to study the spatial configuration of attention. In one such paradigm, an irrelevant stimulus (the cue) is presented in advance of a task-relevant target (Posner, 1980). In a prototypical cueing paradigm, the cue is not predictive of the location of the upcoming target—sometimes the target will appear at the same location as the cue, and sometimes it will not. Nevertheless, response times (RTs) are fastest on trials in which the target is presented at the same location as the cue (i.e. a valid cue), and are slowest on trials in which the target is presented elsewhere (i.e. an invalid cue). This facilitative effect on valid trials is generally thought to occur because attention has already selected the location of the target prior to its

presentation. By comparison, the RT penalty on invalidly cued trials is thought to occur because the processes of deselecting the (attended) cued location and selecting the target take time. The visual system cannot, seemingly, shift instantaneously from enhancing an object at one location to an object at a new location. That is, the cueing paradigm highlights the limited availability of attention to shift across space.

The former is an example of an exogenous cueing study. Exogenous cueing is associated with salience-driven attentional selection because the sudden appearance of the cue seems to trigger its selection automatically. Goal-driven selection can also be studied with the cueing paradigm, this time using an endogenous or symbolic cueing task. Here, cues are usually presented at central fixation. On validly-cued trials, the cue indicates the location of the upcoming target. However, this information must be interpreted by the participant. For example, the letter “O” might be presented if the target will appear to the left, and the letter “H” if the target will appear to the right. On most trials, the cue validly predicts the location of the to-be-attended target. On a subset of trials, however, the target appears at an uncued location, violating the learned cue-target contingency. These are called invalidly cued trials. Neutral trials are also possible—for example, the letter “X” might be presented if the target is equally likely to appear to either the left or right of fixation.

Response times to a target also vary as a function of the time interval separating the onset of the cue and the target (called the cue-target onset asynchrony or CTOA). In exogenous cueing studies, the cueing benefit—that is, the magnitude of the reduction in RTs on valid trials—is greatest if the target is presented within approximately 250 ms of the cue. In endogenous cueing studies, on the other hand, the cueing benefit is greatest if the length of the CTOA is about 800 ms. Salience-driven attentional selection seemingly benefits from a speed of processing advantage. Finally, it should be noted that for exogenous cueing paradigms, the cueing benefit often reverses if the CTOA is increased beyond 300 ms, with RTs now (counterintuitively) longer to valid cues and shorter to invalid cues. This effect has been called inhibition of return, and it is thought to occur because the visual system suppresses recently-attended locations in order to promote the selection of a new stimulus and a different, unattended location (McDonald, Ward, & Kiehl, 1999; Posner & Cohen, 1984; Prime & Ward, 2004).

The second main category of attention experiment involves the brief, sequential presentation of stimuli at a single location. In one variant of this task, participants are shown a series of visual stimuli at central fixation, typically at a rate of ten items per second (i.e. 100 ms/item). This is called the rapid serial visual presentation (RSVP) paradigm. Targets are often implanted within the stream of irrelevant stimuli, and participants are asked to make some form of response to each target. For example, the distractors might be letters of the alphabet and the targets numbers, and participants would be asked to press the corresponding number key on a computer keypad each time they perceive a target. In another variant of this task, the psychological refractory period (PRP) paradigm, there are no nontarget items, but rather two targets presented in sequence (Pashler, 1994). In some variants of this task the targets are masked, such that a noise pattern is overlaid to disrupt the retinal image of the item (Duncan, Ward, & Shapiro, 1994); in other variants, the targets are unmasked (Moore, Egeth, Berglan, & Luck, 1996).

Both the RSVP and the PRP paradigms measure the availability of attention over time (Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992). A critical finding of these paradigms is that if a second target is presented within approximately 200—500 ms of the first target, participants will often fail to respond to it. This phenomenon is called the attentional blink (AB). The AB does not occur simply because of response conflict or some other response-generated effect, but instead because of an apparent reduction in the ability to perceive the second target. As with the inhibition of return effect of the exogenous cueing paradigm, the AB suggests that the visual system cannot always rapidly detect the second of two rapidly presented stimuli. Here, the delay is related not to the time required to select a new location in the visual field, but rather to the time required to process an item at an attended location. That is, the RSVP and PRP paradigms highlight the limited availability of attention over time.

The third general category of attentional paradigm is the visual search paradigm, which is designed to study the deployment of attention in conditions when multiple items of differing salience vie for attentional selection. This paradigm constitutes the experiments presented within this thesis, and as such merits a more detailed introduction, below.

1.1. Attention and visual search

In our everyday lives we often have to find an item of interest in our cluttered visual surroundings. For example, we might look for a particular item on a packed supermarket shelf, our car in the parking lot, or our friend's face in a crowd. This process, of finding a task-relevant *target* among task-irrelevant *nontargets*, is called visual search. These searches can range in difficulty from trivially easy to extremely difficult. Finding your car is easy if there are only a few cars in the lot. It's much harder if your red car is parked alongside dozens of other red cars.

In the laboratory, visual search is usually studied with tasks in which a target and several distractors are presented at random locations on a computer display. In some tasks, the target is present on a proportion of trials (say, 50%) and observers report whether the target is present or absent on the given trial. These are called detection tasks. In other tasks, the target is always present and observers instead have to find the target and make some evaluative judgment of it. For example, in several of the tasks presented in this thesis, observers had to report, via button presses on a computer mouse, whether an item contained a vertical or a horizontal line segment. These are called compound search tasks. Experimentally, detection and compound search tasks differ in a critical task requirement. For detection paradigms, a response can be generated via a single operation—namely, detecting the presence of the target. This single operation is insufficient for compound search tasks, which require the careful scrutiny of the target item. Thus in addition to detecting the target, compound search tasks require additional operations to discern the task-relevant detail of the target. This additional operation results in marked differences in the electrophysiology of attention, which I shall describe in the next section.

To assess the relative difficulty of a given search task, researchers can vary the number of nontargets in the display and measure the resultant change in the amount of time required to find the target. Behavioral measures, including response times (RTs) and accuracy, can be computed as a function of the number of items in the search array (i.e. the display set size). Often, the relationship between RT and set size can be estimated by a positive, linear function. The steepness of this slope—that is, the change in RT per additional item—provides an estimate of the number of items processed by the visual system per unit time. If the slope of the

search function is nearly flat (typically < 10 ms per additional nontarget), search is said to be efficient. Typically, in an efficient search task the target is highly salient and appears to 'pop out' from the rest of the search array. This is the case, for example, when observers are asked to search for a singleton that appears in an otherwise homogenous array of items, such as a green circle among homogenous red circles. If the slope of the search function is greater than about 20 ms per additional nontarget, search is said to be inefficient. In these tasks the target does not pop out from the distractors. Imagine, now, finding the same green circle among red circles and green diamonds. Slopes ranging from 10–20 ms/item are sometimes called 'moderately inefficient' and shall be introduced in greater detail in Chapter 2. It is also possible to obtain negative search slopes in some tasks, such that response times are shorter at larger set sizes. This happens when the presence of additional distractors helps the target pop out (Bravo & Nakayama, 1992). For example, Utochkin (2013) reported negative search slopes in a search task in which a color singleton target was presented among heterogeneously colored distractors. The distractors were rendered from a limited palette of colors (three maximum); thus as set size increased, the distractors duplicated. This promoted a color discontinuity between the distractors and the target, which made the target easier to find at large set sizes.

The reason why search difficulty varies is not entirely understood, and remains the focus of active study. In the 1980s, Ann Treisman and her colleagues published a series of highly influential articles that linked selective attention to distinct stages of visual processing (Treisman & Gormican, 1988; Treisman & Gelade, 1980). This account, feature integration theory (FIT), divided visual perception into two stages. In the initial stage of processing, basic visual features such as color, line orientation and direction of movement are extracted from the field of view. At this stage, processing of these visual features is performed at all locations simultaneously and by distinct, dedicated areas within visual cortex. In the subsequent stage of processing, these basic visual features are combined, at a single locus within the field of view, into a perception of a whole object. These two stages are typically called the pre-attentive and the attentive stage, respectively.

One of the benefits of FIT was that it elegantly accounted for differences in efficient and inefficient visual search tasks. Let us consider efficient search tasks first, as they are the more straightforward of the two from a theoretical standpoint. Because the time to find the target is

unaffected by the number of elements in the search array, vision researchers agree that in these conditions the processes mediating search must be operating, simultaneously and without capacity limitations, on all items in the display. This is called parallel selection. Returning to the previous example, if yours is the only red car in the parking lot then you can find it with the same speed regardless of whether there are ten, twenty, or one hundred green cars around it. Parallel selection is possible because, at an early stage, the visual system computes certain coarse differences in visual information (Itti, Koch, & Niebur, 1998; Itti & Koch, 2001). This phenomenon is strongly linked with salience-driven attentional selection, in that if the visual discrepancy between one item and all other items is sufficiently large, the item pops out automatically. According to FIT, the detection of this item is not thought to require attention; that is, detection of a unique-feature item is thought to be pre-attentive.

By comparison, if your car shares similar features to other cars—say, form and color—then search becomes more inefficient. At the level of attentional processing, the difference between the target (your car) and the nontargets is insufficient to be identified pre-attentively. In these situations, it is thought that attention must be invoked to resolve these visual discrepancies, by selecting the features at a given locus and binding them together into a veridical percept. This cohesive item can then be compared against a mental template of the target. If the attended item is not the target then attention is redeployed to a new locus, and this process repeats until either the target is found or search is abandoned. This would explain why RT increases with set size, as the visual system randomly selects and inspects an ever-increasing number of distractors until the target is found by chance. This item-by-item inspection is called serial selection.

Treisman and her colleagues ascribed efficient and inefficient search to parallel and serial selection, respectively. However, this strict dichotomy has been heavily critiqued over the ensuing years (e.g. Townsend, 1990). Generally, most of these criticisms focus on the fact that behavioral data do not provide unequivocal evidence for seriality of processing. As a result, others have presented various alternative ways in which inefficient search could result from parallel item selection (e.g. Bundesen, 1990). Although there is no question that observers selectively process items in a serial fashion when scanning the environment with successive eye movements (i.e. overt search), it remains debated whether inefficient search tasks require serial

deployments of attention when the eyes remain fixed (covert search; for an excellent introduction to this topic see Woodman & Luck, 2003).

1.2. The electrophysiology of visual search

Many researchers have turned to electroencephalography (EEG) and the event-related potential (ERP) technique to investigate the neural origins of selective attention. Briefly, the EEG signal recorded from a scalp electrode represents the summation of excitatory and inhibitory post-synaptic potentials from many thousands of proximal cortical pyramidal neurons. When these neurons receive numerous post-synaptic potentials, of the same polarity and within a few milliseconds, the graded electrical fields interact constructively and become sufficiently large to project through neural tissue, meninges, skull, and scalp.

A cognitive operation of interest can be analyzed quantitatively using an event-related approach. In this type of analysis, changes in the EEG can be computed for a time period of interest relative to a neutral baseline. Usually, this is done by comparing the EEG elicited by a stimulus to a brief period immediately preceding the onset of that stimulus. When analyzed this way, the event-related EEG contains both the electrical signal of the cognitive operation of interest, and a substantial amount of task-irrelevant electrical noise. As a general rule, the magnitude of the noise exceeds that of the signal of interest by roughly one order of magnitude. Given though that noise, by definition, varies randomly over time, it can be attenuated by averaging together the recordings taken from many hundreds of trials. After averaging across many hundreds of trials and across many participants, any remaining electrical perturbations in the resultant grand average must have been present across a significant proportion of trials. This remaining signal is called the event-related potential (ERP), and it reflects the isolated electrical responses of whatever cognitive processes are required for a given task. The resultant ERP is often contrasted across experimental conditions and measured in several ways. For example, its latency can be compared in order to determine if a given processes occurred earlier (or later) under different conditions. Similarly, its amplitude can be compared to determine if an experimental manipulation led to a change in the magnitude—or in the duration—of a cognitive process. The ERP approach offers extremely high temporal resolution (millisecond

accuracy), but because it reflects the summated activities of a large number of neurons, its spatial accuracy is typically worse than metabolic imaging modalities such as magnetic resonance imaging and positron emission tomography.

The earliest electrophysiological evidence that selective attention modulates neural activity was provided not in the visual domain, but in audition. Historically, auditory tasks have been well suited for the study of covert attention because humans cannot move their ears to better perceive a sound. In a study performed by Hillyard and colleagues (Hillyard, Hink, Schwent, & Picton, 1973), participants were presented streams of auditory tones in each ear, and were instructed to respond to a target pip from one ear but not the other. The neural effect of selective attention was assessed by comparing the auditory N1 waveform elicited by the target in the attended ear versus the corresponding waveform elicited by the nontarget—but otherwise physically identical—tone in the unattended ear. Although the N1 was present to both target and nontarget tones, it was markedly larger in amplitude for attended tones. Thus, the results demonstrated that attention operates, seemingly, by enhancing the fundamental processes controlling sensory processing. They also highlight that attention interacts to affect sensory processing at a very early stage, at least in the auditory domain.

To isolate the electrophysiological processes mediating visual attention, it is necessary to first identify and dissociate overt and covert shifts of attention. The first study to do this was performed by Voorhis and Hillyard (1977). Participants responded to targets presented in a designated visual hemifield and ignored items presented in the other, ignored hemifield. Electrodes were placed lateral to the outer canthus of each eye and were referenced electrically to each other. The voltage of this horizontal electrooculogram is approximately zero microvolts when the eyes are positioned straight ahead, and becomes positive or negative when the eyes shift to the left or right. During the experiment, observers were instructed to maintain their gaze at all times on a central fixation point. Thus, trials in which observers made an eye movement to the target could be identified and selectively excluded from the ERP analysis.

With this analysis technique, Voorhis and Hillyard (1977) were able to provide the first unequivocal evidence that attention also modulates neuroelectric responses in the visual domain. Attended and unattended targets both elicited P1 and N1 responses in the ERP

waveforms recorded at posterior-occipital electrodes, however the amplitudes of these responses were larger for attended items. The application of attention seemed to “turn up” the amplitude of the underlying ERP waveform, like in the auditory domain. Similar results were also observed in cueing paradigms, both with informative symbolic cues (Mangun & Hillyard, 1991) and with nonpredictive peripheral cues (Hopfinger & Mangun, 1998); in each case, targets elicited a larger visual P1 component on valid-cue trials than on invalid-cue trials.

Collectively, these results indicate that, in vision, the earliest electrophysiological consequence of attention occurs about 100 ms post stimulus. However, this was in conditions in which attention was already directed to a particular location in advance of the target. In a typical visual search paradigm though, the observer does not know in advance where the target will be presented. Presumably, this additional step of directing attention to the location of the target should delay the earliest electrophysiological effects of attention. In a series of seminal experiments, Luck and Hillyard (1994a, 1994b) investigated ERP effects as observers located a pop-out target presented among homogenous distractors. To ascertain that any ERP differences were the result of attention, as opposed to lower-level imbalances in sensory processing, all displays contained an equal number of items in both the left and right visual field (i.e. a balanced search array). On target-present trials, the ERP waveform became more negative at posterior-occipital scalp electrodes contralateral to the target. This negative difference emerged at the approximate latency of the visual N2, and was therefore termed the *N2 posterior contralateral* (N2pc). The amplitude of the N2pc was found to be sensitive to target-distractor similarity, such that it was larger on trials when the target was more difficult to discern from the distractors. It was also found to be larger in amplitude in compound search tasks than in detection tasks. Thus, early theories held that the N2pc reflected some operation that suppressed or attenuated the representation of nearby distractors. This explanation was challenged in a subsequent study conducted by Eimer (1996), which found that the N2pc could be observed with just a single distractor. Given the near-total absence of distractors in that search task, Eimer (1996) countered that the N2pc more likely reflects the selective enhancement of the target by attention.

Recently, several studies from our research group have investigated the cognitive processes reflected by the N2pc. The first was a study performed by Hickey and colleagues

(Hickey, Di Lollo, & McDonald, 2009), which exploited the lateralized nature of the N2pc in a two-item visual search task. The processes mediating target selection were isolated by placing the target in a lateral visual field and the distractor on the vertical midline (items on the vertical midline do not contribute to a lateralized ERP component). A robust negative difference was observed beginning at approximately 200 ms, which the authors termed the *target negativity* (N_T). Similarly, the processes mediating distractor suppression were isolated by placing the distractor in a lateral visual field and the target on the vertical midline. Now, rather than a contralateral negativity, the ERP waveform was relatively more positive contralateral to the distractor. The authors termed this the *distractor positivity* (P_D). A subsequent study by (Gaspar & McDonald, 2014) sought to further characterize the relationship between the N_T , P_D and N2pc. The authors used a uni-dimensional search task in which the target and a highly salient distractor were defined within the same visual dimension (namely, color). The distractor could be either present or absent. A larger N2pc was observed on distractor-present trials, and the isolated amplitudes of the target N_T and distractor P_D summed to almost exactly equal that of the N2pc. Collectively, the results suggest that the N2pc reflects processes involved in both the enhancement of the attended item and the suppression of salient distractors.

Jannati et al. (2013) provided a context for the stage at which the N2pc might occur during a typical visual search task (Figure 1-1). First, pre-attentive processes operate on basic visual features, such as line orientation, color, and luminance. Relative differences in these features are computed to derive a salience map of the overall display, and the location of the most salient item is identified. Following this, attentive processes are invoked to apprehend a selected item. The visual system first selects a location for attention, and attention filters the contents of the selected locus in order to resolve visual ambiguities. The visual system can then transfer the selected item into an object detection pathway, and the observer ultimately determines whether the attended item is—or is not—the target. If the item is not the target, or if another item must be attended, then the entirety of the attentive stage is repeated. Presumably, this repetition of the attentive stage would elicit multiple N2pc responses in the grand-averaged ERP waveform. This concept shall be considered in greater detail in Chapters 2 and 3.

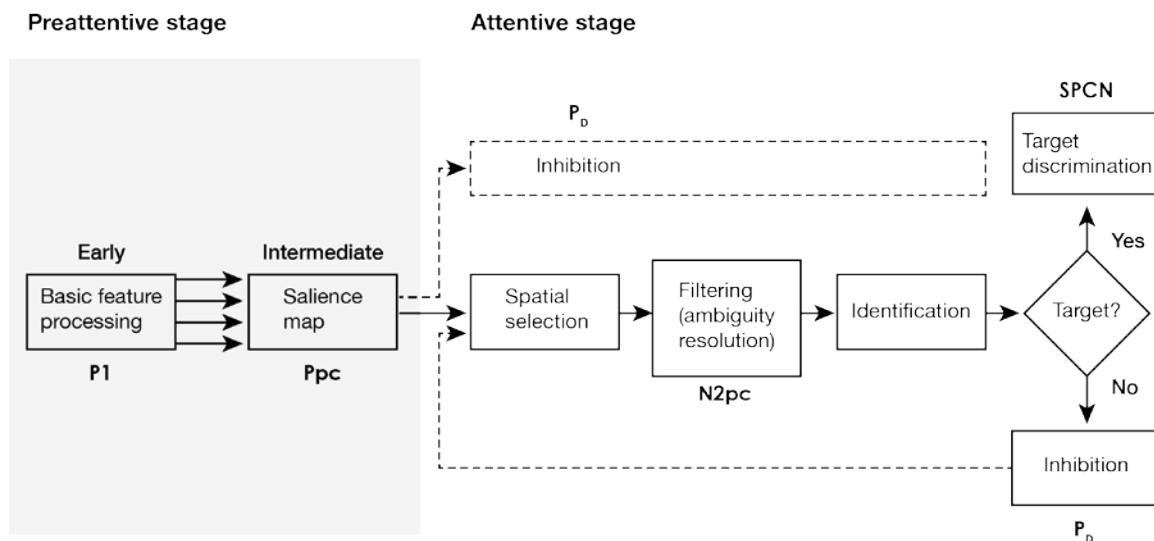


Figure 1-1. Sequence of cognitive processes during compound visual search. Adapted from Jannati, Gaspar and McDonald, 2013 (with permission).

1.3. The present thesis

This thesis investigated how bottom-up (i.e. exogenous) and top-down (i.e. endogenous) factors influence attentional object selection. To that end, several experiments were conducted which systematically modified the saliency of the items in the search display, the attentional set of the observers, or both. The timing of object selection was examined using behavioral, oculomotor and electrophysiological measures. Chapter 2 sought to determine whether relevant but non-salient items could ‘pop-out’ at the level of attentional selection, and to determine whether search for such items is accomplished serially or in parallel. This was done by equating bottom-up saliency across target and nontarget items. In this way, the target could not be identified on the basis of its physical saliency alone—a powerful bottom-up factor. Chapter 3 takes the opposite approach: here, task relevance was equated across multiple items in order to investigate the effects of saliency on selection. In the absence of a top-down guiding signal, the order of attentional selection would only be biased by relative differences in the bottom-up saliency of the search items. Chapter 4 follows on Chapter 3 by investigating how bottom-up and top-down factors interact by encouraging the initial selection of a less-salient target singleton.

Chapter 2. Multiple-Singleton Visual Search

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2.1. Abstract

The time required to find an object of interest in the visual field often increases as a function of the number of items present. This increase, or inefficiency, was originally interpreted as evidence for the serial allocation of attention to potential target items, but controversy has ensued for decades. We investigated this issue by recording event-related potentials from humans searching for a target in displays containing several differently colored items. Search inefficiency was ascribed not to serial search but to the time required to selectively process the target once found. Additionally, less time was required for the target to “pop out” from the rest of the display when the color of the target repeated across trials. These findings indicate that task-relevance can cause otherwise inconspicuous items to pop out, and highlight the need for direct neurophysiological measures when investigating the causes of search inefficiency.

2.2. Introduction

Visual search is said to be efficient or inefficient depending on whether or not additional time is required to find the target as the number of display items (set size) increases (Wolfe, 2003; Wolfe & Horowitz, 2004). In perfectly efficient search tasks, no additional search time is incurred by increasing the set size; in this case the function relating reaction time (RT) to set size (herein called the set-size function) is flat. In very inefficient search tasks, RTs increase sharply as additional items are added to the display, with search slopes in excess of 30 ms per item (Pashler, 1998). Several theories of attentional selection have been proposed to explain these variations, but the causes of search efficiencies are not yet clear.

Search is hypothesized to involve two general stages of visual processing: an early, pre-attentive stage in which items are processed in parallel and the saliency of these items is

computed; and a later, attentive stage in which items are selected individually for further analysis (Desimone & Duncan, 1995; Itti & Koch, 2001; Neisser, 1967; Theeuwes, 2010; Treisman & Gelade, 1980; Wolfe, 1994). According to this two-stage framework, efficient search occurs when the pre-attentively computed salience of just one item – the target – is high enough to compete for attention. This is the case, for example, when the target is a feature singleton appearing in an array of identical distractors. The target attracts attention effortlessly in such situations; that is, it is said to “pop out” (Bravo & Nakayama, 1992). This type of search is often called *parallel search*, because processing at the early, parallel stage is sufficient to locate the target. If observers must foveate or identify the target, they may then deploy attention directly to its location (Bichot, Rossi, & Desimone, 2005). Set-size functions are often still flat in this latter type of search (herein called *direct search*), indicating that once the target pops out, it can be selected automatically (Bravo & Nakayama, 1992; Theeuwes, 1992).

Whereas flat set-size functions have been attributed to parallel search, positive set-size functions have most often been ascribed to *serial search* (Treisman & Gelade, 1980). Such inefficient searches can occur, for example, when the target shares similar visual features with the distractors or is defined by the absence of a specific feature (Treisman & Souther, 1985). In the context of the two-stage processing framework, the computed salience of the target is no longer higher than that of any other display item, and in the absence of a strong bias toward the target, attention must be deployed serially to multiple items in the display until the target is found (Figure 2-1, top row).

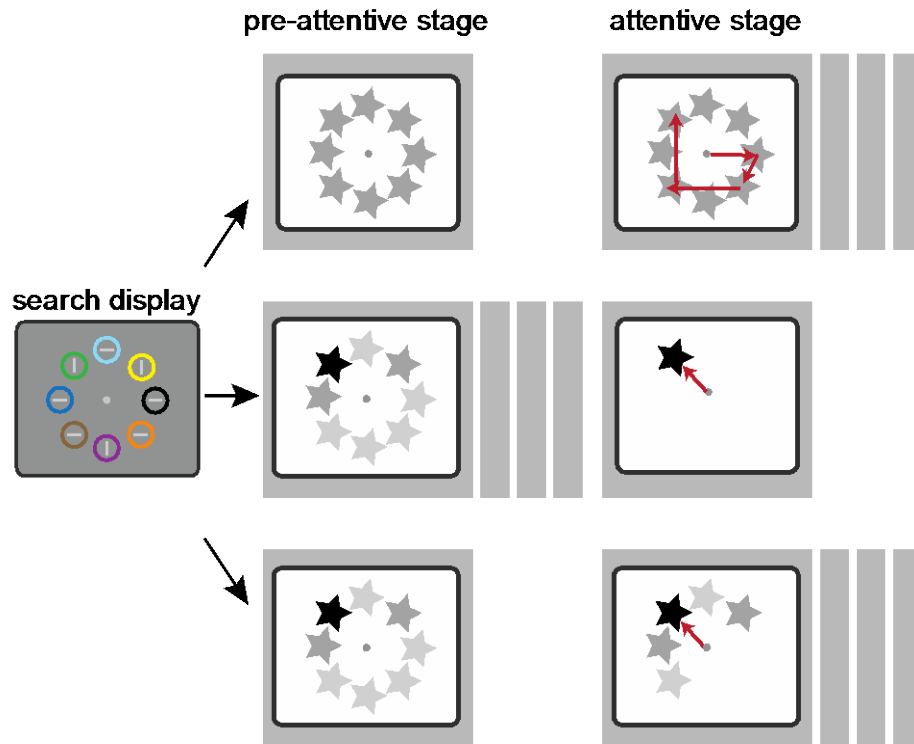


Figure 2-1. Hypothetical causes of inefficient visual search for a green target in a multiple-singleton display. The broken, shaded region in each row highlights the stage at which processing is hypothesized to be inefficient. Top row: Serial search. Middle row: Inefficient pre-attentive processing. Bottom row: Inefficient attentive processing. See text for details.

Several lines of evidence illustrate that search can be direct or serial under different conditions. For example, when humans and monkeys are free to move their eyes during search for a feature-singleton target, they move their eyes directly to the target on the vast majority of trials (e.g. (Bichot & Schall, 1999; Findlay, 1997; Ogawa & Komatsu, 2004). In contrast, when human observers must identify a subtle feature of a target in the presence of a very similar non-target, they first shift attention to one of the items and then, if necessary, re-deploy attention to the other item after 100 ms (Woodman & Luck, 1999, 2003). Although this latter pattern of results is consistent with serial search, it does not indicate that the positive search slopes obtained in more typical search tasks are due to multiple deployments of attention. In fact, the serial-search explanation for such positive slopes has faced stiff opposition. The general

objection is that a positive set-size slope could arise from a variety of inefficiencies and thus does not provide unequivocal evidence for serial search (Townsend, 1990).

Figure 2-1 illustrates two alternative ways in which an increase in set size could lead to inefficient search. First, the presence of additional distractors might prolong the pre-attentive processes required to single out the target as the most salient item in the display (Figure 2-1, middle row). This would delay the subsequent deployment of attention but would not necessitate serial inspection of multiple items (Bichot & Schall, 1999; Folk & Remington, 1998). Second, the presence of additional distractors might prolong attentive processes required to resolve the target's identity, while leaving the duration of pre-attentive processes and the time at which attention is first deployed to the target unaffected (Figure 2-1, bottom row). Unfortunately, these alternatives and the conventional serial-search explanation all make similar predictions about the slope of the set-size function, thereby making it difficult for researchers to pinpoint the cause of inefficient search on the basis of behavioral data alone.

To address the possible sources of search inefficiency, we recorded event-related potentials (ERPs) from human observers performing a multiple singleton search task (Anderson, Laurent, & Yantis, 2011; Belopolsky & Awh, 2013). Participants searched for a red or green target that appeared among several heterogeneously colored distractors. Critically, this task pits against each other two factors that influence search performance in opposite ways: (i) *distractor heterogeneity*, which makes search less efficient, and (ii) *target uniqueness*, which makes search more efficient (Wolfe & Horowitz, 2004). To uncover the sources of any search inefficiency, we measured the onset and amplitude of a neuroelectric component called the N2pc, which reflects attentional selection of an item in a visual search array (Hickey, Di Lollo, et al., 2009; Luck & Hillyard, 1994b; Luck & Kappenman, 2012). In typical singleton search tasks, the N2pc emerges approximately 180–200 ms after the onset of the search display, regardless of set size (Mazza, Turatto, & Caramazza, 2009).

Target singletons can also elicit the N2pc when the display contains another, nontarget singleton (Gaspar & McDonald, 2014; Jannati, Gaspar, & McDonald, 2013; Luck & Hillyard, 1995; McDonald, Green, Jannati, & Di Lollo, 2013; Wykowska & Schubö, 2010). This latter finding suggests that the visual system can automatically select a task-relevant singleton even when it

is no more salient than one other item in the visual field. In the present study, we asked whether the visual system can select a target singleton when *all* of the display items are singletons, and thus all items are nominally equal in salience.¹

The present study investigated the timing and amplitude of the N2pc as a function of set size (Experiment 2-1) and inter-trial repetition (Experiment 2-2). Search performance was inefficient in Experiment 2-1, but the electrophysiological results showed that set size did not influence the timing of attentional deployment. Here, search inefficiency was linked not to serial search but to the duration of attentive processes required to select the target (selection time). The results of Experiment 2-2 showed that the target was attended sooner on color-repeat trials than on color-change trials – an effect known as priming of pop out (Maljkovic & Nakayama, 1994). These results support the following conclusions: (i) task-relevance can cause otherwise inconspicuous items to pop out, at least when those items possess unique attention-guiding features, and (ii) inefficiencies in search performance are not always caused by serial search.

2.3. Methods

The Research Ethics Board at Simon Fraser University approved the experimental procedures used in this chapter.

2.3.1. Experiment 2-1

Participants.

Twenty-two observers participated in Experiment 2-1 after giving informed consent. Data from four participants were excluded from the analysis because >35% of the trials were rejected due to eye movements, blinking, or amplifier blocking, leaving 18 participants (8 male,

¹ A singleton is an item that possesses one attribute that sets it apart from all other items (Egeth & Yantis, 1997). Although this term is typically used when just one item possesses a unique feature and the remaining items are all identical, we use the term to refer to any stimulus that possesses a unique feature. By this definition, visual search displays can contain just one singleton (typical feature search tasks), two singletons (e.g., the additional singleton paradigm; Theeuwes, 2010), or any number of singletons (Bacon & Egeth, 1994; Theeuwes, 2004)

mean age 20.7 years, 3 left handed) in the grand average. Ten different observers (4 male, mean age 19.6 years, one left handed) participated in a control task (Experiment 2-1b) after giving informed consent. In both experiments, participants reported normal or corrected-to-normal vision and were screened for colorblindness using Ishihara color plates.

Apparatus.

The experiment was conducted in a dimly lit, acoustically and electrically shielded chamber illuminated by DC-powered LED lighting. In Experiment 2-1, participants sat 57 cm from a computer monitor operating at a resolution of 800×600 pixels and an 85 Hz vertical refresh. In Experiment 2-1b, participants sat 57 cm from an LCD monitor operating at a resolution of 1920×1080 pixels and a 120 Hz refresh, the performance of which is suitable for both psychological testing and ERP time-locking (Lagroix, Yanko, & Spalek, 2012). Stimulus presentation was controlled by Presentation (Neurobehavioral Systems Inc, Albany, CA) from a Windows-based computer. In Experiment 2-1, the EEG was recorded using custom software (Acquire) from a second Windows-based computer, using a 64-channel A-to-D board (PCI 6071e, National Instruments, Austin, TX) connected to a high input impedance EEG amplifier system (SA Instruments, San Diego, CA).

Stimuli and Procedure.

Search displays consisted of four, six, eight, or ten items spaced equally around an imaginary circle (12.6° radius) centered on a fixation point. The search array was presented for 2,500 ms or until participants made a response. For the three largest set sizes, two items were located on the vertical meridian, one above and one below fixation. The items were colored, unfilled circles (2.2° radius) containing lines of either a vertical or horizontal orientation ($2.27 \times 0.4^\circ$). The background of the display was medium gray (18.5 cd/m^2), and the lines and fixation point were light gray (40.1 cd/m^2). The target was either a red (8.3 cd/m^2 , $u' = .59$, $v' = .36$) or a green (25.9 cd/m^2 , $u' = .27$, $v' = .61$) circle. In Experiment 2-1, only one of these target colors appeared on a given trial; in Experiment 2-1b, half the trials contained either a red or a green target (each with 25% frequency), and half the trials contained neither a red or a green target). The colors of the distractor circles were selected at random from a set of either nine (Experiment 2-1) or ten (Experiment 2-1b) highly discriminable colors (cyan, yellow, black, orange, purple,

brown, blue, magenta, white, and turquoise in Experiment 2-1b), such that no distractor color appeared more than once in the display.

Each trial began with a fixation point displayed for 500 ms, followed by the search display. The search display would remain visible for 2500 ms or until a response was registered. In Experiment 2-1, participants reported the orientation of the line inside the target circle by pressing one of two buttons on a standard computer mouse with the index and middle fingers of their dominant hand. In Experiment 2-1b, participants were instructed to ignore the orientation of the line segments and to instead indicate the presence or absence of the red or green target. We required participants to search for one of two potential targets in order to maintain consistency with Experiment 2-2 (where two target colours were required) and with a previous study (Anderson et al., 2011). The number and color of the distractor circles varied pseudo-randomly across trials within each block so that each set-size appeared 25% of the time. Orientation of the line contained within the target circle also varied pseudo-randomly. Participants received training on 48 practice trials, and completed 25 blocks of 48 trials of the search task.

Electrophysiological recording and analysis.

EEG signals were 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, and five nonstandard sites inferior to the standard occipital electrodes. All EEG signals were referenced to the right mastoid. EEG and EOG were amplified with a gain of 20,000 within a pass-band of 0.01–80 Hz and were digitized at 500 Hz. A semi-automatic procedure was performed to remove epochs of EEG that were contaminated by eye movements, blinks, and amplifier blocking. Artifact-free data were then used to create averaged ERP waveforms, which were digitally low-pass filtered (-3 dB cutoff at 30 Hz) to remove high-frequency activity. The averaged event-related HEOG did not exceed 2 μ V for any individual participant, indicating that gaze remained within 0.3° of the fixation point for most trials (McDonald & Ward, 1999).

ERPs were computed separately for the four-, six-, eight-, and ten-item search arrays in which the target was presented in a lateral visual field and in which observers correctly evaluated the line segment within the target. ERPs were computed relative to a 100-ms pre-stimulus baseline. For each participant, the ERP waveforms were collapsed across left and right visual hemifields and left and right electrode sites to create waveforms recorded contralateral and ipsilateral to a lateral target. Lateralized ERP difference waveforms were then derived for each condition by subtracting the ipsilateral waveform from the corresponding contralateral waveform using lateral occipital electrode sites (PO7 and PO8). Negative voltages were plotted upward such that the N2pc would appear as an upward deflection in these difference waveforms. The mean N2pc amplitude was computed from the contralateral-minus-ipsilateral difference wave in the 200–260 ms post-stimulus interval, and its onset latency was computed using a jackknife method as the point at which the difference waveform reached 50% of its peak amplitude in the 75–400 ms interval (Miller, Patterson, & Ulrich, 1998; Ulrich & Miller, 2001).

2.3.2. Experiment 2-2

Participants.

Thirty-one new observers participated after providing informed consent. Data from five participants were excluded, leaving 26 participants in the grand average (11 male, mean age 22.5, 3 left-handed).

Apparatus.

The apparatus was identical to those in Experiment 2-1b.

Stimuli and procedure.

Stimuli were similar to those used in Experiment 2-1, with the exception that the display set size was fixed at eight items and no items were displayed on the vertical meridian. At the start of each trial, participants specified the color that was to be used for the target by pressing the green or red button on a gamepad (Logitech, Newark, CA). This was done to ensure that participants were always consciously aware of the color of the upcoming target. Participants were encouraged to follow a 'RRGG' (or 'GGRR') pattern when specifying the target color. This

was done to ensure roughly equal color-repeat and color-change trials. The search display appeared 800–1200 ms after participants selected the target color. Following the display onset, participants were asked to report the orientation of the line contained within the target circle by pressing one of two shoulder buttons on the game pad.

For one half of the experiment, participants searched for the red or green target among heterogeneously colored distractors (as in Experiment 2-1; multiple-singleton condition), and in the other half they searched for the target among homogenous distractors of the opposite color (i.e. red target among green distractors; green target among red distractors; one-singleton condition). Task order was varied across participants. Participants completed 14 blocks of 64 trials, for a total of 896 experimental trials, and participants completed 32 practice trials of both the multiple-singleton and feature-search conditions.

Electrophysiological recording and analysis.

EEG acquisition was as described for Experiment 2-1, with the exception that signals were instead recorded from 25 Ag/AgCl electrodes positioned at FP1, FPz, FP2, F7, F3, Fz, F4, F8, T7, C3, Cz, C4, T8, P7, P3, Pz, P4, P8, PO7, POz, PO8, O1, Oz, O2 and M1. ERPs were computed from artifact-free trials in which observers correctly evaluated the orientation of the line segment within the target. ERPs were computed separately for the multiple-singleton and one-singleton conditions and for trials in which the color of the target either repeated or changed. The method for analyzing the ERPs was as described in Experiment 2-1, except that the mean N2pc amplitudes were computed in 50 ms intervals centered on the negative peaks in the contralateral-minus-ipsilateral difference waveforms for the four conditions. The mean amplitudes of the P1 and N1 were computed by averaging the contralateral and ipsilateral waveforms from 90–130 ms and from 160–200 ms post-stimulus, respectively.

2.4. Results

2.4.1. Experiments 2-1 and 2-1b: Efficient attentional selection despite inefficient search performance

Participants searched for a red or green circle (target) that appeared along with a varying number of differently colored circles (distractors; see Figure 2-1). Each circle contained a horizontal or vertical line segment, and participants were required to indicate the orientation of the line segment inside the target (i.e., compound search; (Duncan, 1985). Because all circles were color singletons, the target was no more or less conspicuous than the distractors. Consequently, no item popped out from the rest of the array based on physical salience alone. The target's uniqueness was still relatively high, however, because it possessed a unique color (a strong guiding visual attribute Wolfe & Horowitz, 2004). Prior research indicates that participants may set themselves for a specific target feature under such conditions (called *feature-search mode*; Bacon & Egeth, 1994). Here, the hypothesized feature set would have to include both red and green because these different-colored targets were presented unpredictably across trials.

To assess the efficiency of search performance, we analyzed RT for correct-response trials across the four set sizes using a one-way analysis of variance (ANOVA; after excluding 12.8% of trials due to oculomotor artifact). RTs were found to increase with set size, $F(3, 51) = 54.50, p < .001$. The slope of RT \times set size function was 15 ms per item (Figure 2-2A), which is similar to the slopes obtained in other multiple-singleton search tasks (Bacon & Egeth, 1994; Theeuwes, 2004). Observers also committed more errors as set size increased, $F(3,51) = 4.39, p = .008$, indicating that a speed-accuracy trade-off did not occur (Table 2-1). These results indicate that search performance was moderately inefficient.

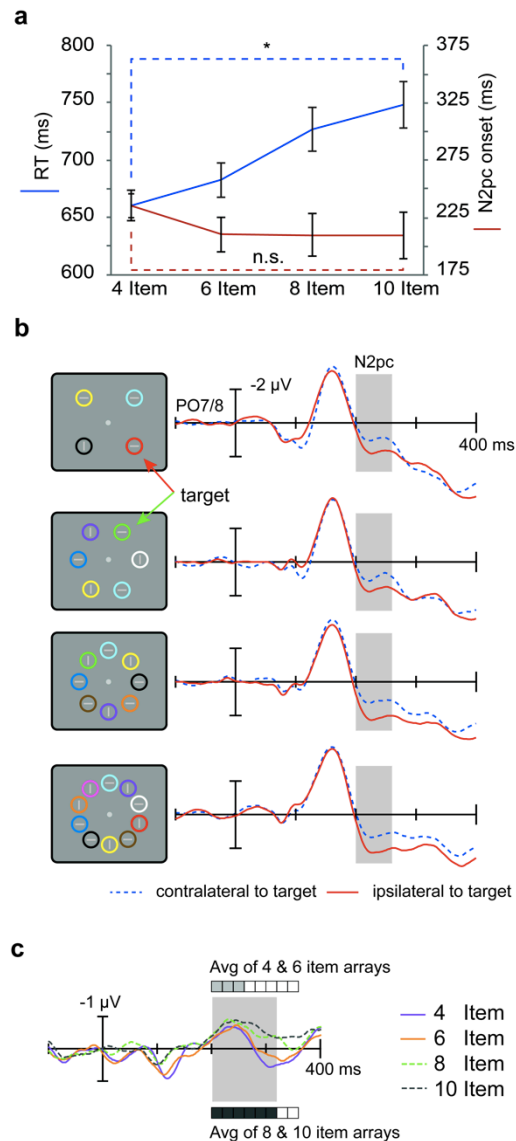


Figure 2-2. Experimental task and main results for Experiment 2-1. (a) Mean RT increased with larger set sizes (15 ms/item), but the onset of the N2pc remained constant regardless of set size. (b) Grand-average ERPs elicited by the 4-, 6-, 8-, and 10-item search displays. The target (red or green circle) elicited an N2pc in all conditions. (c) Contralateral-Ipsilateral difference waveforms based on the ERPs shown in panel b. The difference waves were constructed such that the N2pc is seen as an upward (negative) peak. There was no significant difference in the onset or magnitude of the N2pc across the four set sizes, but the duration of the N2pc was significantly longer for the two larger set sizes than for the two smaller set sizes.

To ensure that that the positive set-size slope was not caused by the use of a compound search task, we collected RTs in a detection variant of this multiple singleton search task (Experiment 2-1b). This control experiment was similar to Experiment 2-1, except that displays contained a target (green or red circle) on only 50% of the trials. Participants were instructed to

determine whether one of the targets was present or whether both were absent. As in Experiment 2-1, RTs increased with set size, $F(3,27) = 47.91, p < .001$. Participants were also faster to respond on target-absent trials than on target-present trials, $F(1,9) = 24.44, p < .001$. Critically, on target-present trials the slope of the set size function in this detection task (12 ms/item) was not significantly different than that obtained in the main, compound search task, $t(26) = 1.04, p = .31$. Thus, the inefficiency in search performance cannot be ascribed to the usage of a compound search task.

Table 2-1. Median Correct Response Times (RTs) and Error Rates by Experimental Condition

Experiment / Condition	Median RT (SEM), ms	Error rate (SEM), %
Experiment 2-1		
4-item	660 (13.5)	5.1 (0.7)
6-item	683 (14.9)	6.1 (0.9)
8-item	727 (18.9)	7.5 (1.0)
10-item	748 (20.4)	7.4 (1.1)
Experiment 2-2		
Multiple singleton, color repeat	761 (18.4)	5.2 (1.2)
Multiple singleton, color change	882 (27.8)	8.0 (1.5)
Feature search, color repeat	685 (14.4)	3.3 (0.5)
Feature search, color change	773 (21.3)	4.4 (0.9)

The hypotheses illustrated in Figure 2-1 lead to contrasting predictions about how an increase in set size would influence the target-elicited N2pc in Experiment 2-1. First, if search is serial and unguided (Figure 2-1, top row), little or no N2pc would be observed in the ERP waveform after averaging all trials. This is because an unguided serial search would trigger multiple, successive N2pc waves on each trial – that is, a different N2pc would be triggered each time attention was focused on a different item (Woodman & Luck, 1999, 2003). Critically, the N2pc waves elicited when attention is deployed to items in the non-target hemifield would counteract the N2pc waves elicited when attention is deployed to items in the target hemifield,

leaving no overall N2pc in the averaged ERP waveform. Second, if an increase in set size prolongs processing at the early, parallel stage but does not impair direct search (Figure 2-1, middle row), an increase in set size would delay the onset of the target N2pc but would not otherwise influence N2pc amplitude or duration (Wykowska & Schubö, 2011). Third, if an increase in set size prolongs processing involved in selecting the target but does not influence early, parallel processing or the time at which target selection begins (Figure 2-1, bottom row), an increase in set size would prolong the duration of the target N2pc without delaying its onset. Finally, if multiple singleton search is completely efficient at least until the selection stage has been completed, increasing set size would have no effect on search performance or the target N2pc waveform.

Analysis of the ERP waveforms elicited by the different-sized search arrays revealed four key results (Figure 2-2B). First, the N2pc was in evidence for all four set sizes, disconfirming the purely serial search explanation. The amplitude of the N2pc differed significantly from zero in the 200–260 ms interval (all $t > 2.35$, all $p < .031$). Second, the amplitudes and onset latencies of the N2pc waves were found to be statistically indistinguishable across the four set sizes, $F_s < 1$. Critically, the set-size function for N2pc onset latency was flat (numerically: -4 ms/item; Figure 2-2A). Thus, despite the behavioral evidence for inefficient search, these electrophysiological results indicate that the target popped out at the level of attentional selection. Third, although the onset latency of the N2pc was invariant, the duration of the N2pc varied as a function of set size. For the N2pc duration analysis, new waveforms were computed by averaging the contralateral-minus-ipsilateral difference waveforms of the two smaller arrays and the two larger arrays. The resultant waveforms (not shown) were then t-tested against zero, in 20 ms intervals, from 200–360 ms (dark gray boxes on the abscissa in Figure 2-2C). This analysis confirmed that the duration of the N2pc was significantly longer for the large arrays (200–320 ms) than for the small arrays (200–260 ms). A paired-samples t-test also revealed that the N2pc was more negative for the two large arrays in the 260–320 ms interval, $t(17) = 2.74$, $p = .014$.

The fourth major ERP result was that for the two smaller set sizes, a contralateral positivity was present in the 125–150 ms interval. This posterior, contralateral positivity (Ppc) is typically observed when a singleton target is presented among homogenous distractors and has been hypothesized to reflect bottom-up salience (Fortier-Gauthier, Moffat, Dell'Acqua,

McDonald, & Jolicœur, 2012; Jannati et al., 2013). In the present study, the Ppc was found to differ significantly between set sizes, $F(3,51) = 3.76, p = .016$. A post-hoc T-test revealed that the Ppc was significantly larger for the two smaller arrays (averaged together) than the two larger arrays, $t(17) = 2.91, p = .010$.

In sum, the ERP results from Experiment 2-1 indicate the following: (i) processing at the early, parallel stage was efficient; (ii) attention was deployed directly to the target in the same amount of time for 4-, 6-, 8- and 10-item arrays; (iii) attentional selection was prolonged for larger displays. In other words, the search inefficiency in this task is attributable to increased attentional selection time.

2.4.2. Experiment 2-2: Inter-trial priming of pop-out facilitates multiple-singleton search

Experiment 2-1 showed that the timing of the pre-attentive stage of processing is not affected by display set size. This is consistent with the hypothesis depicted in the bottom row of Figure 2-1, in which search inefficiency is linked to an increase in the duration of the attentive stage. Experiment 2-2 was performed to further understand this particular processing stream. Specifically, we sought to determine if the timing of either the pre-attentive or attentive stages could be influenced by selection history.

Previous studies have shown that the repetition of a target's features from one trial to the next facilitates search for a singleton under typical pop out conditions (that is, when one salient singleton appears among a homogenous set of nontargets; (Maljkovic & Nakayama, 1994). It has been hypothesized that this inter-trial *priming of pop-out* occurs because selection of the target features on trial n biases the visual system towards selection of those same features on trial $n+1$ (Awh, Belopolsky, & Theeuwes, 2012). This biasing is thought to occur via facilitation of the pre-attentive stage of processing (Lee, Mozer, & Vecera, 2009). Consistent with this interpretation, inter-trial priming leads to an earlier N2pc, indicating that target singletons are selected sooner when their features repeat across successive trials than when their features change, at least when the target is set against an array of homogenous distractors (Eimer, Kiss, & Cheung, 2010).

In Experiment 2-2, we sought to determine if inter-trial priming would facilitate target selection in the multiple-singleton search task. In other words, we asked whether priming of pop-out would facilitate selection of the target, even when none of the items popped out on the basis of bottom-up salience. Here, participants searched for a red or green target in a fixed array of eight items. On each trial, participants selected the color of the upcoming target by pressing either a green or a red button on a standard computer gamepad. Participants were instructed to follow a 'RRGG' (or 'GGRR') pattern to ensure an equal number of color-repeat and color-change trials. This was done to ensure that participants knew the color of the upcoming target. In one half of the experiment, the target was presented among heterogeneously colored distractors, as in Experiment 2-1. We refer to this as the *multiple-singleton* condition. In the other half of the experiment, the target was presented among homogenous distractors of the opposite color (i.e. a red target among green distractors, or vice versa). We refer to this as the *one-singleton* condition.

In all, 16.5% of trials were excluded due to oculomotor artifact. Participants responded correctly on 94.8% of the remaining trials. Behavioral and electrophysiological effects were quantified based on target type (color repeat vs. color change) and condition (multiple singleton vs. one singleton). Consistent with the priming of pop-out effect, RTs were faster on color-repeat trials than on color-change trials, $F(1,25) = 106.29, p < .001$. The magnitude of this priming was larger in the multiple-singleton condition (122 ms) than in the one-singleton condition (88 ms), as evidenced by a significant target type \times condition interaction, $F(1,25) = 8.72, p = .007$. Participants also committed more errors on target change trials, $F(1,25) = 16.83, p < .001$, indicating that a speed-accuracy tradeoff did not occur (Table 2-1).

Figure 2-3A displays contralateral-minus-ipsilateral difference waves obtained in the two conditions, collapsed over color-repeat and color-change trials. Each waveform contained a prominent N2pc in the same general time range, beginning \sim 200 ms post-stimulus and lasting until approximately 320 ms. Statistical analysis revealed that the N2pc onset latency for the multiple-singleton condition (222 ms) did not differ from that of the one-singleton condition (213 ms) $t_{corrected}(25) = 1.54, p = .14$. To assess N2pc duration, we again computed mean amplitudes in consecutive 20-ms intervals from 200 ms to 360 ms (dark gray boxes on the abscissa in Figure 2-3A). Each N2pc was found to be significant until 300 ms post-stimulus. These

analyses indicate that the timing of the N2pc was very similar across the two conditions. By contrast, mean N2pc amplitude was found to be significantly larger for the multi-singleton condition than in the one-singleton condition in the 225-275 ms interval, $t(25) = 2.76, p = .011$. Given that N2pc amplitude has been linked to selection difficulty (Luck, Girelli, McDermott, & Ford, 1997), these results indicate that it took more effort to filter out the differently colored distractors than the uniformly colored distractors.

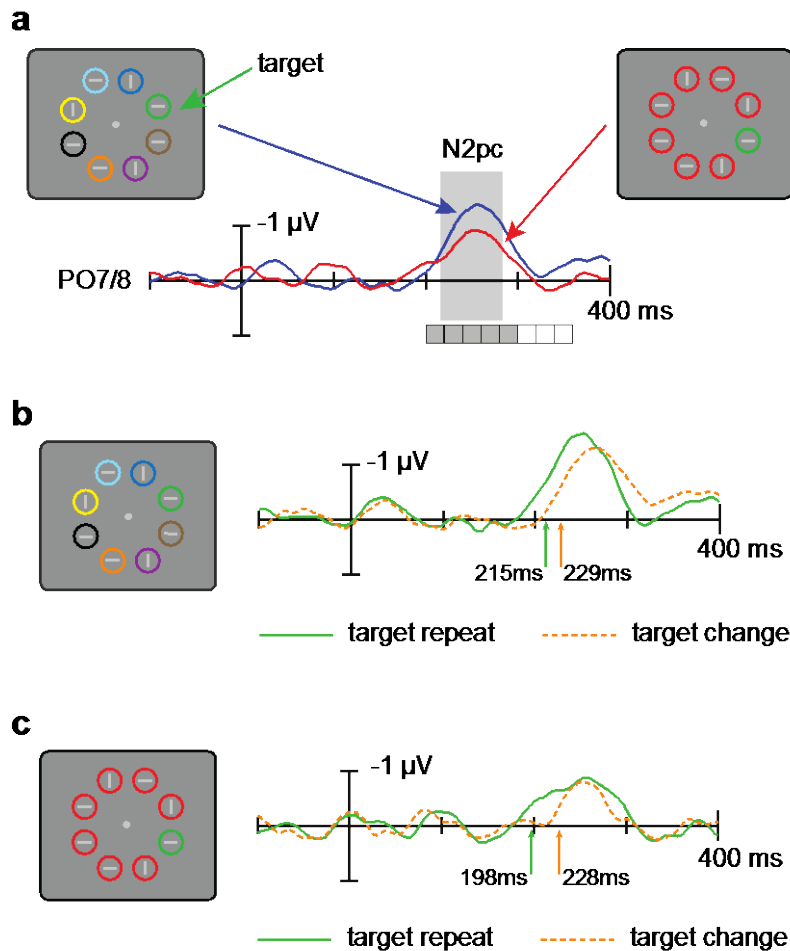


Figure 2-3. Experimental task and electrophysiological results for Experiment 2-2. (a) Ipsilateral-minus-contralateral difference waveforms for the multiple-singleton (blue) and one-singleton (red) conditions. The amplitude of the N2pc was larger for the multiple-singleton condition, however neither the onset nor the duration of the N2pc differed between conditions (gray boxes on abscissa). Difference waveforms in (b) the multiple-singleton condition and (c) the one-singleton condition when the color of the target repeated (green) or changed (orange dashed) trials. For both conditions, the N2pc was earlier on color-repeat trials, but did not differ in amplitude.

Figures 2-3B and 2-3C present the difference waveforms obtained on color-repeat and color-change trials. Critically, the onset of the N2pc was earlier on color-repeat trials (206 ms) than on color-change trials (228 ms), $F_{corrected}(1,25) = 29.91$, $p < .001$, confirming that priming of pop-out facilitated attentional selection of the target. The onset of the N2pc was unaffected by condition, and the condition \times target type interaction was nonsignificant. These results indicate that the heterogeneity of distractor color had no influence on the magnitude of the inter-trial priming of pop-out.

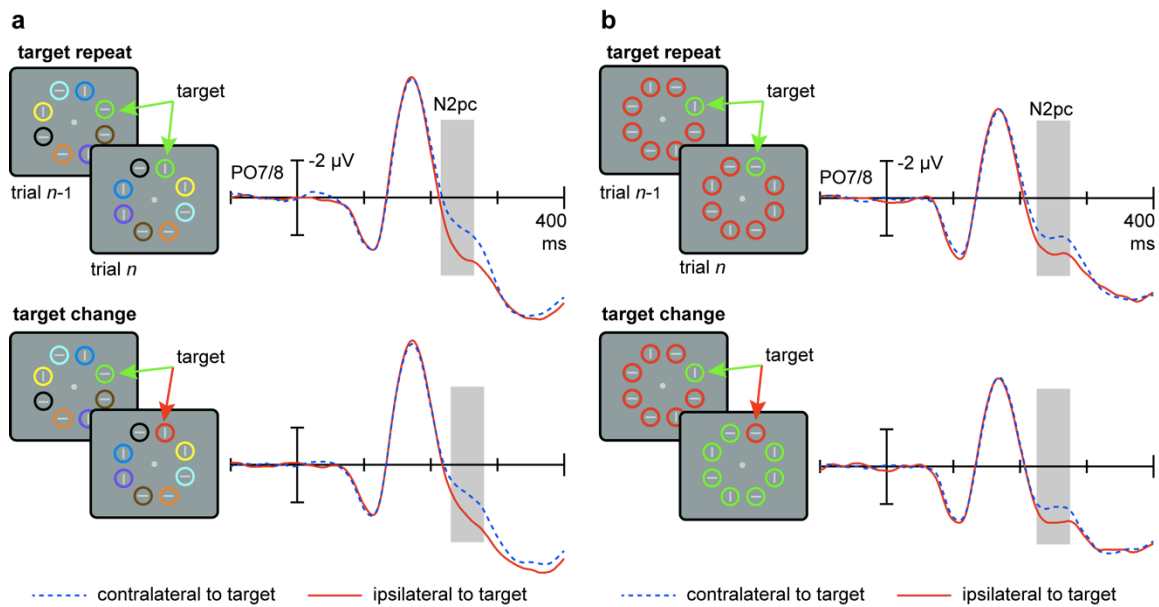


Figure 2-4. Electrophysiological results from Experiment 2-2 for (a) the multiple-singleton condition, and (b) the one-singleton condition. In both conditions, the amplitudes of the P1 and N1 components were not significantly different when the color of the target repeated (top row) relative to when the color of the target changed (bottom row).

Whereas inter-trial priming influenced the timing of N2pc onset, it did not appear to influence N2pc amplitude, which was statistically indistinguishable on color-repeat and color-change trials (the target type \times condition interaction was also nonsignificant). These results indicate that although target selection was delayed on color-change trials, selection was no more difficult when target color changed from one trial to the next than when it repeated across successive trials.

So far, the earliest effect of priming appeared to be a 22-ms shift in N2pc onset latency (see also Eimer et al., 2010). To determine whether this was indeed the earliest effect, we measured the amplitudes of the P1 and N1 components of the ERP waveforms recorded contralateral and ipsilateral to the target in each condition (Figure 4). The P1 and N1 amplitudes were found to differ across search conditions: the P1 was larger in the one-singleton condition ($2.01 \mu\text{V}$) than in the multiple-singleton condition ($1.62 \mu\text{V}$), $F(1,25) = 9.50$, $p = .005$, whereas the N1 was larger in the multiple-singleton condition ($-5.24 \mu\text{V}$) than in the ones-singleton condition ($-4.80 \mu\text{V}$), $F(1,25) = 11.06$, $p = .003$. Critically, each of these early sensory-evoked ERP components was similar in amplitude for color-repeat and color-change trials, all $F < 1$,

confirming that the earliest electrophysiological cost of a color change occurred in the interval of the N2pc.

In sum, Experiments 2-1 and 2-2 provide converging evidence that the task-relevant target contained in multiple-singleton search displays does in fact pop out at the level of pre-attentive processing. As a result, the target can be found by direct attentional selection, and does not require serial deployments of attention – despite the positive set size slope observed in Experiment 2-1, a result that has frequently been used to infer seriality of processing.

2.5. Discussion

For several decades, researchers have examined how set size affects search performance to determine whether search in any given task is efficient or inefficient. Traditionally, efficient and inefficient patterns of performance were associated with parallel search and serial search, respectively. More recently, researchers have conceptualized a continuum of inefficiency rather than a strict dichotomy between efficient and inefficient search tasks (Wolfe, 1998), but the underlying neural causes of inefficiency are still largely unknown. Here, we used the ERP method to uncover the cause of inefficiency in a multiple singleton search task. Performance was found to be moderately inefficient when set size was varied (Experiment 2-1). Although such inefficient performance has been attributed to serial inspection of multiple items (Theeuwes, 2010; Treisman & Gelade, 1980; Treisman & Souther, 1985), the ERP results obtained in the present study showed that attention was deployed directly to the target, regardless of the number of items in the display. Search inefficiency was attributed not to serial search but to increased attentional selection time for displays containing more distractors.

In Experiment 2-1, set size modulated the duration of the N2pc but not the onset latency or amplitude of the N2pc. At first glance, the absence of an N2pc amplitude effect appears to be at odds with previous studies in which N2pc amplitudes increased as set size increased (Luck et al., 1997; Mazza et al., 2009). It is likely that this apparent discrepancy is due to the contrasting way in which set size was increased: In previous studies, set size was increased by adding

identical nontarget items to the display, whereas in the current study, set size was increased by adding unique nontarget items to the display. In the former case, the target may have been easier to find when set sizes were large due to the enhanced gradient discontinuity provided by the more uniform background (nontarget) items. Such enhanced gradient discontinuities are often associated with negative – rather than positive – search slopes: RTs actually get shorter as set size increases (Bravo & Nakayama, 1992). Mazza et al. (2009) did observe negative search slopes in some of their search conditions, indicating that the target was indeed easier to find when the set size was increased. In contrast, the gradient discontinuity would be minimal in the present study because the target appeared on a heterogeneous array of nontarget singletons regardless of set size. On this basis, we suspect that the set-size effects on N2pc amplitudes observed in previous studies may have been related to the increased ease with which the target could be located.

In the context of visual search, “pop-out” is said to occur when one item can be differentiated from other items in the search array effortlessly. The term is usually associated with singleton search tasks in which target uniqueness is maximized and distractor heterogeneity is minimized. Contemporary models of visual search ascribe pop-out to physical factors that boost stimulus salience (e.g., local contrast, see Itti & Koch, 2001; Theeuwes, 2010; Wolfe & Horowitz, 2004). By this account, an item that is physically dissimilar to neighboring items pops out. Such bottom-up pop-out cannot occur in the multiple-singleton search task because all items are distinct, and thus no one item captures attention on the basis of its physical uniqueness. Still, the ERP results of Experiment 2-1 were consistent with efficient search. On this basis, we conclude that making one of many singletons relevant causes that item to pop out even though it is no more salient than its neighbors. This conclusion is consistent with models of visual search that permit top-down attentional guidance. For example, the guided-search model (GS4) proposes that a match between a display item and the attributes of the stored target representation can lead to efficient search (Wolfe, 2007).

The pop out that occurred in Experiment 2-1 was found to be susceptible to inter-trial priming in Experiment 2-2. Typically, this inter-trial priming is observed with conventional pop-out displays containing a singleton target set against an array of homogenous distractors. The results from the present study show that inter-trial priming of pop-out extends to

inconspicuous objects made salient by task relevance, at least when the target possesses a unique guiding feature. Beyond this main finding, two aspects of the results are worth noting here. First, the priming effects were in evidence even though participants determined the color of the target on every trial. That is, knowledge of the upcoming target color did not eliminate the cost of switching target color. This is in line with the conclusion that priming of pop-out is reflexive and cognitively impenetrable (Maljkovic & Nakayama, 1994). Second, the difference in N2pc onset latency (~200–230 ms) was the earliest difference between the ERPs on color-repeat and color-change trials. There was no difference in amplitude or latency of the earlier P1 or N1 components. This is in line with the conclusion that although priming of pop-out facilitates the deployment of attention to repeated features, it does not enhance earlier perceptual-level processing of those features (Lee et al., 2009).

The present results highlight the utility of the ERP method in determining the exact origin of search inefficiency. It has been proposed – and it is generally well accepted among researchers – that an item possessing a unique color can strongly guide attention towards its location (Wolfe & Horowitz, 2004). The means by which such strong guiding attributes affect attentional deployment is unclear, however. Here, the ERP results establish that in the presence of a strong guiding feature, search inefficiency was minimal and was linked specifically to selection times. This result dovetails with a pair of recent ERP studies in which search inefficiency was instead linked to the pre-attentive stage when the target was defined by a weaker guiding attribute. Specifically, N2pc latency was found to increase with set size when the task was to search for a form singleton or for a target defined by a conjunction of features (Wolber and Wascher, 2003; 2005). This pattern of results is perfectly in line with the prediction stemming from our own pre-attentive-inefficiency hypothesis (see Figure 2-1, middle row). Finally, results of another recent study suggest that search can be serial when the target is defined by the absence of a feature, at least when search displays are very brief and set size varies randomly across trials (Dowdall, Luczak, & Tata, 2012, Experiment 1). When averaged across all trials, the ERPs contained no hint of N2pc in this case. This latter finding is in line with the prediction stemming from the serial-search hypothesis (see Figure 2-1, top row). Search thus becomes serial when there is no feature that can be used to guide attention towards the target.

The challenge in determining the cause of inefficient search based on RTs alone is also highlighted in a debate about the deployment of attention in multiple-singleton search tasks. In these tasks, the target is defined by a unique feature (a singleton), but some or all of the distractors are also singletons (as in Experiment 2-1). Because the target is not the only unique item, observers cannot reliably locate it by detecting a discontinuity in the search array. Instead, observers must set themselves to search for the defining feature of the target (feature search mode). The adoption of a feature-search mode leads to relatively inefficient search performance, as evidenced by a positive search slope in the 10–15 ms/item range. Based on this moderate slope, some researchers proposed that this feature search mode requires serial deployments of attention (Theeuwes, 2004), whereas others proposed it can be performed entirely in parallel (Bacon & Egeth, 1994). The approach used in the present study avoids such dichotomization by addressing inefficiencies at various stages of processing. The present findings are inconsistent with a purely serial mechanism underlying color-based feature search mode, but the increased selection time observed in Experiment 2-1 shows that search in this task is not perfectly efficient.

Chapter 3. Oculomotor Tracking During Two-Target Visual Search

3.1. Abstract

Chapter 2 investigated the mechanisms controlling selective attention in a visual search task in which the target was no more or no less physically salient than the distractors. As a result, physical salience was coarsely equated across all items and observers could only locate the target by configuring their attentional parameters appropriately. A key finding was that the target “popped out” at the level of pre-attentive processing, which permitted its rapid selection regardless of the number of items in the search display. Top-down attentional control, in other words, made the target salient—even though bottom-up salience was, broadly, equated.

Chapter 3 follows on this by addressing the opposite question—namely, whether or not salience confers a processing advantage when top-down guidance is equated. To address this question, attentional selection was tracked overtly as observers inspected two items of differing physical salience: one a highly salient color singleton and the other a less salient shape singleton. Top-down guidance was equating by making both items equally task relevant, and thereby eliminating any benefit from initially inspecting either item. The results from Chapter 3 reveal that observers made discrete fixations to both singletons, and that the order of selection was heavily biased by salience, with the more salient of the two targets selected first. This confirms that stimulus-driven effects can fundamentally drive attentional selection in the absence of top-down guidance.

3.2. Introduction

At any given moment, the locus of attentional selection is biased by two complementary control mechanisms. The first control mechanism biases selection towards physically salient stimuli, such as a flash of light or a sudden movement. This is often called stimulus-driven selection. The second control mechanism biases selection towards stimuli that match our top-down goals, such as when you search for your friend's face in a crowded room. This is often called goal-driven selection. In many real-world conditions, these two control mechanisms are thought to interact to ultimately influence what stimulus is selected by visual attention at any given moment.

Many experiments have studied the effects of stimulus- and goal-driven selection using a category of visual search task called the additional singleton paradigm (ASP). In the ASP, observers are presented displays containing several homogenous distractors and a target defined by a unique feature (i.e. a singleton). For example, the target might be a green diamond and the homogenous distractors green circles. On a proportion of trials (usually 50%), the search display also contains a singleton distractor of greater nominal salience than the target, such as a red circle. Response times (RTs) to the target are significantly slower if displays contain this salient distractor than if displays do not contain this salient distractor (Theeuwes, 1992), and this is thought to occur because of conflict between goal-driven selection processes (for the target) and stimulus-driven selection processes (for the singleton distractor).

An early and influential theory accounted for this RT penalty in the context of a *salience-driven capture* of attention. By this account, if an observer is confronted by a complex scene containing numerous items, the initial deployment of attention will always be to location of the most salient item (see Theeuwes, 2010, for a review). This deployment is reflexive and cannot be prevented by goal-driven selection, and it is only following this initial capture that goal-driven processes can shift the locus of attention from the most salient item to the target. In the previous example of visual search, this means that attention automatically selects the salient distractor, even if participants know in advance that this item is task irrelevant.

This salience-driven capture account has faced stiff opposition from many attention researchers, and a long-standing debate has considered whether salient stimuli automatically capture attention or whether top-down control can partially prevent capture (e.g. Folk, Remington & Johnston, 1992). Paralleling the issues raised in Chapter 2, this debate emerged in part because indirect behavioral measures, such as RTs, cannot unambiguously measure the mechanisms controlling attentional selection. Subsequent studies have attempted to resolve this debate by allowing participants to move their eyes freely and by measuring these overt shifts of attention with eye tracking. If the search display does not contain the salient distractor then saccades are made directly towards the target, as would be expected. If however the display does contain the singleton distractor then saccades to the target follow a curvilinear trajectory. The vertex of this curved saccade varies substantially from one trial to the next, being towards the singleton distractor on some trials and away from the singleton distractor on others. Typically, eye movements are made towards the distractor if the saccade is initiated very quickly after the onset of the search display, whereas eye movements are made away from the distractor if the saccade is initiated more slowly after the onset of the search display (van Zoest, Donk, & Theeuwes, 2004). Although these findings clearly demonstrate that a salient distractor affects eye movements, it remains unclear why an eye movement curves towards or away from a salient distractor on a given trial. In a recent review, Van der Stigchel and colleagues interpreted *both* patterns of data in favor of salience-driven capture (Van der Stigchel, Meeter, & Theeuwes, 2006). Specifically, eye movements towards the distractor were interpreted to reflect a biasing effect towards salient stimuli (van Zoest & Donk, 2005), consistent with the idea of salience-driven capture, and eye movements away from the distractor were interpreted to occur from an inhibitory mechanism that down-weighs a particular location following capture (Godijn & Theeuwes, 2004).

Thus far, studies that have investigated salience-driven and goal-driven selection have done so by putting these two selection mechanisms in opposition to each other. In the ASP, any RT cost imparted by the presence of the singleton distractor can therefore be confidently ascribed to salience and not to task relevancy, given that the distractor is not task relevant. Although there is universal agreement that the salient distractor affects response speed in the ASP somehow, it remains debated whether this truly reflects salience-driven attentional capture. Moreover, behavioral measures such as RT must be registered after the processing of

all information necessary to generate a response. As a result, they cannot unambiguously track the locus of attentional processing during search.

An alternative account has framed attentional object selection in terms of a combination of stimulus salience and task relevance (for recent reviews see (Bisley & Goldberg, 2010; Fecteau & Munoz, 2006). According to this account, the items in a search display are assigned a priority based on both their physical salience and based on whether they possess a task-relevant feature. In the case of the ASP, the salient distractor is occasionally assigned greater priority (on the basis of its salience) than the target (on the basis of its task relevance), resulting in the (inappropriate) initial selection of the distractor. On other trials, the target is assigned higher priority than the distractor, resulting in the (appropriate) initial selection of the target. Unfortunately, this priority queue account, and other accounts such as salience-driven selection, make similar predictions about the pattern of RT data in the ASP.

In order to disentangle these accounts, it is necessary to modify the ASP in a manner that equates goal-driven selection between the two singletons. In such a task, any experimental difference could be ascribed, with confidence, to stimulus-driven selection processes alone. Thus, the present study implemented a variant of the ASP with two critical modifications. First, all trials contained both a highly salient color singleton and a less salient shape singleton. Second, goal-driven selection was equated by making both singletons task relevant. Specifically, participants were asked to inspect both singletons and report whether line segments contained within were similar or dissimilar in orientation. Participants were instructed to move their eyes freely in performing this task, and the locus of attentional selection was measured directly using an eye tracker.

There were two main experimental predictions. On the one hand, if selection is fundamentally biased by salience, as predicted by salience-driven selection, participants should initially saccade to the color singleton before the shape singleton, even though doing so would confer no strategic benefit. On the other hand, if salience-driven selection does not occur then the initial eye movement should be made to either singleton at random, consistent with the fact that both singletons are equally task relevant.

3.3. Materials and Methods

The Research Ethics Board at Simon Fraser University approved the experimental procedures used in this chapter.

3.3.1. Participants

Nineteen observers (mean age 20.4 years, 8 male, 3 left handed) participated in Experiment 3-1 after providing informed consent. All participants reported normal or corrected-to-normal vision and were screened for colorblindness using Ishihara color plates.

3.3.2. Apparatus

The experiment was conducted in a dimly lit, acoustically isolated room. Participants sat 57 cm from a computer monitor operating at a resolution of 800 × 600 pixels and an 85 Hz vertical refresh. Stimulus presentation was controlled by Presentation (Neurobehavioral Systems Inc, Albany, CA) from a Windows-based computer. Ocular data were recorded from the right eye using a desk mounted, high-resolution eye tracking system operating at a 1,000 Hz sampling rate (EyeLink 1000, SR-Research, Ottawa, ON).

3.3.3. Stimuli and Procedure

Prior to the commencement of the main task, participants, under supervision, were asked to subjectively match the brightness of the color red to the color green, until the participant was satisfied that the two were isoluminant. The process was repeated four times, and the average red value used subsequently. The stimuli in the visual search task were presented against a black background, and a fixation dot measuring $0.5 \times 0.5^\circ$ visual angle was presented at all times during the experiment. Each trial consisted of two screens: a blank intertrial display containing only the fixation dot and the search display. The search display consisted of six stimuli 2.3° in diameter and arranged equidistant along an invisible circle with a radius of 5° . Each search display contained four task-irrelevant distractor circles (e.g. green), a single shape target singleton (e.g. green diamond), and a single color target singleton (e.g. red

circle). Within each stimulus there was a vertical or a horizontal line segment measuring 1.1° , and participants had to respond via a button response if the lines contained within the two targets were pointed in the same or in different directions. The search array was presented for 4,000 ms or until participants responded, and participants were asked to respond “as quickly as possible while minimizing errors”. Colors were consistent across all trials for each participant, and were counterbalanced across participants. Participants were encouraged to move their eyes naturally in order to complete the task, but were not encouraged to follow any particular pattern of eye movements or fixations (i.e. they were not encouraged to initially inspect either singleton).

Each block of 32 trials contained an equal number of trials in which the color target was presented in a lateral visual hemifield and the shape target on the vertical visual meridian (lateral color, midline shape), in which the shape target was presented in a lateral visual hemifield and the color target on the vertical visual meridian (lateral shape, midline color), in which both the color and the shape target were presented in the same lateral visual hemifield (fully ipsilateral), and in which the color and shape targets were in opposing visual hemifields (fully contralateral). Trials were randomly shuffled by the experimental computer, and participants completed 15 blocks of 32 trials.

Drift and offset were corrected by having participants complete a nine-point calibration routine at the beginning of every new block of trials. A new trial would not commence until participants return their gaze to the fixation cross and maintained it there for a random duration of 800–1,200 ms.

3.3.4. Data analysis

Saccadic response times (SRTs), the duration of gaze fixation, and the order of target inspection were computed from blink-free, correct-response trials. Saccades were identified using a detection algorithm as the point at which an eye movement’s velocity exceeded $30^\circ/s$ and its acceleration exceeded $8,000^\circ/s^2$; fixations were defined as the point at which an eye movement dropped below these thresholds.

For each trial, two circular regions of interest (ROIs) with a radius of 4.5° were defined around each of the two singletons. SRTs were computed as the time at which the first saccade landed within each ROI, time-locked to the appearance of the search display.

3.4. Results

On average, 3.1% of trials were rejected from the analysis due to incorrect response and a further 4.5% of trials were rejected due to blinking.

Average response speed across all trial types was 1,328 msec (SEM = 63.1 msec), which is notably slower than in the typical additional singleton paradigm (cf. Theeuwes, 1992). In the standard ASP, response speeds are computed as a function of the presence or absence of a highly salient distractor. Here however, each trial always contained a highly salient color singleton and a less salient shape singleton, which precludes such an analysis. However, the distance between these two items did vary unpredictably from one trial to another, and an additional behavioral analysis was done to determine if RT varied as a function of target-target distance. RTs were therefore recomputed for trials in which the two targets were located either adjacent to each other (Distance 1), were separated by one nontarget (Distance 2) or were separated by two nontargets (Distance 3). These results are depicted in Table 3-1. A significant difference in RT was observed as a function of target-target distance, $F(2,36) = 4.12, p = .025$. Error rate did not vary as a function of target-target distance, $F(2,36) = 2.22, p = .12$, suggesting that participants did not exchange accuracy for speed in this task. Bonferroni-corrected post-hoc comparisons revealed an inconsistent pattern of results however, with the only significant contrast ($p < .05$) being between RTs for Distance 2 versus Distance 3 trials.

Table 3-1. Median Correct Response Times (RTs) and Error Rates

Target-Target Distance	Median RT (SEM), ms	Error rate (SEM), %
Distance 1 (adjacent)	1320 (61.4)	3.17 (0.50%)

Distance 2	1343 (65.3)	3.23 (0.56%)
Distance 3	1304 (66.6)	2.37 (0.58%)

The primary goal of this chapter was to determine whether the order of overt inspection was biased by salience. This research question is predicated on the assumption that observers made two discrete fixations, one at each singleton. Therefore, it is necessary to first rule out two alternative accounts of attentional object selection: (i) if participants completed the task without making an eye movement away from central fixation (that is, covertly); (ii) if participants completed the task by making a single saccade, either to one singleton (but not the other) or to an interstitial location between the two singletons (that is, a global effect).

To investigate these two possibilities, the data were analyzed to determine the percentage of trials in which observers fixated only the color singleton or only the shape singleton (but not the other). Observers fixated only the color singleton on 10.8% of trials and only the shape singleton on 9.0% of trials, with neither singleton being fixated more often than the other, $t(18) = 1.22, p = .24$. Next, the data were analyzed to determine the percentage of trials in which observers fixated neither of the singletons—either because gaze did not shift from central fixation or because observers fixated an undefined region of interest. This accounted for 4.8% of all trials. Finally, the data were analyzed to determine the percentage of trials in which observers fixated both singletons. This rate, 75.4%, was significantly greater than the rate of fixating just one singleton or neither singleton, $F(2,36) = 50.7, p < .001$. Thus, this analysis confirms that observers fixated both target singletons on the majority of trials.

The next stage of analysis sought to determine whether salience biased the order of attentional selection between these two targets. Here, the analyses were restricted to trials in which observers fixated both singletons. First, the latency of the initial saccade to each singleton was computed (saccadic RT). If salience did not bias the order of selection, then this measure should have been approximately equal between the two targets. Instead, saccadic RTs were markedly faster to the color singleton target (436 msec) than to the shape singleton target (640 msec), $t(18) = 6.35, p < .001$. The difference between these two saccadic RTs ($SRT_{color} - SRT_{shape}$) also provides an estimate of the time required to redeploy attention from one target to

another: about 204 ms. Second, the percentage of trials was computed in which the first fixation was made to the color singleton. A one-sample T-test confirmed that observers made an initial fixation at the color singleton (72.6%) significantly more frequently than chance alone, $t(18) = 9.11, p < .001$. Collectively, this confirms that salience consistently biased the order of object selection.

Next, the amount of time participants fixated each target was computed (i.e. ocular dwell time). This was done to determine if the observed differences in saccadic RT were accompanied by differences in the duration of a fixation at each singleton. There was a trend towards greater dwell time at the color singleton (378 msec) than at the shape singleton (357 msec), however this effect was only significant at the one-tail level, $t(18) = 1.92, p = .071$. Since this was not predicted a priori, we conclude that ocular dwell times did not vary significantly between the two singletons.

Finally, an additional analysis was performed to further investigate the previously reported RT finding that participants were slowest to respond when the two targets were separated by a single distractor (Target-target distance 2). To determine if this behavioral effect was linked to slower fixations from one target to the other, saccadic RTs were analyzed using a repeated-measures ANOVA with three levels of the factor Distance (1, 2 or 3) and two levels of the factor Singleton (color singleton, shape singleton). The results of this analysis are depicted in Table 3-2. As expected, sRTs were significantly longer to the shape singleton than to the color singleton, $F(1,18) = 165, p < .001$. Mirroring the behavioral effect, sRTs also varied with target-target Distance, $F(2,36) = 6.86, p = .003$. Further investigation revealed that selection speed of the color singleton was unaffected by target-target distance, but that selection of the shape singleton was slower on Distance 2 trials relative to Distance 1 trials, $F(2,36) = 6.57, p = .009$. Thus, the oculomotor results support the conclusion that observers were slower to shift attention from the color singleton to the shape singleton at a target-target distance of 2, even though this effect was not predicted a priori.

Table 3-2. Mean Saccadic Response Times (RTs)

Target-Target Distance	Color singleton sRT (SEM), ms	Shape singleton sRT (SEM), ms
Distance 1 (adjacent)	422 (18.0)	627 (26.4)
Distance 2	442 (20.6)	666 (31.6)
Distance 3	427 (20.0)	644 (38.1)

3.5. Discussion

In Chapter 3, observers located two singletons, one a highly salient color singleton and the other a less salient shape singleton, and made an evaluative comparison of the two items. Critically, the design of this experiment equated the two singletons for task relevance. In so doing, it obviated the need for the goal-driven selection of one singleton over the other, or to select one singleton before the other. Because of this, it can be reasonably inferred that the order of attentional object selection would proceed randomly—on a trial-by-trial basis, observers would initially (and unpredictably) select either the color or the shape singleton first. Instead, the results of Experiment 3-1 revealed that selection was consistently and predictably biased by relative salience. Observers selected the color singleton before the shape singleton on the majority of trials, and saccadic RTs were markedly faster to the color singleton than to the shape singleton. On the basis of these effects, it is clear that salience biases the priority for attentional selection, at least in those cases when the most salient item is irrelevant and thus to be ignored.

Discrete ocular dwell times were observed at each of the two targets. This suggests that attention was applied discretely to each of the two targets—that is, serially. Moreover, the speed of object reselection was found to be approximately 200 ms, a value broadly consistent with several other measures of multiple object selection (Moore et al., 1996; Theeuwes, Godijn, & Pratt, 2004; Woodman & Luck, 1999, 2003). Although not a primary goal of this experiment, this finding relates to the long-standing debate about whether fine visual perception is possible

for multiple items at multiple locations (parallel selection) or is restricted to a single item at a single location (serial selection; Townsend, 1990). In the additional singleton paradigm (ASP), observers often make saccades to a location between the two singletons (called a *global effect*, see Van der Stigchel et al., 2006). These interstitial selections could occur because the salient distractor biased the eye movement, such that the programmed saccade landed outside the to-be-inspected object. Alternatively, this could occur because the salient distractor was partially (and covertly) selected for additional scrutiny by observers. In the standard ASP it is not possible to disentangle these two accounts. Here however, the results clearly support the conclusion that observers made discrete fixations at each object on the majority of trials, a finding that is arguably more consistent with serial object selection. However, eye movements cannot unambiguously reveal “purely serial” deployments of attention from partially overlapping object selection. This issue is far from academic: many real-world estimates of object processing estimate that the visual system can process about 30 items per second (Wolfe, 1998), but attentional dwell time experiments suggest that attention can only be redeployed about five times per second (Moore et al., 1996; Theeuwes et al., 2004; Woodman & Luck, 1999). It has been proposed that visual processing can be accomplished through a hybrid of serial and parallel item selection (Wolfe, 2007). However, oculomotor data cannot unambiguously disentangle serial selection from hybrid serial/parallel selection. This issue will be explored in greater detail in Chapter 4.

3.5.1. On salience-driven attention capture

The current study confirmed that the order of attentional object selection is profoundly biased by salience—the most salient item within the field of view will be selected first, if all other things are equal. At first pass, this is conceptually consistent with the theory of automatic, salience-driven capture of attention. According to this theory, object salience is computed rapidly and early, and biases subsequent object selection. Top-down control cannot override this initial, salience-driven selection (Theeuwes, 2010). However, many real-world search conditions involve an interplay between stimulus- and goal-driven selection, and it does not necessarily follow that top-down control cannot override initial salience-driven selection.

There is little question that salience can affect initial stimulus processing, nor is there any question that top-down modulation can be slow to influence stimulus processing. For example, a study by Ogawa and Komatsu (2004) investigated the underlying neural mechanisms of object selection in monkeys trained in the ASP. Neurons in area V4 responded more robustly to a color singleton than to a shape singleton within the first 175 ms of stimulus presentation. Moreover, the rate of neuronal activity was identical whether the monkey was searching for the color singleton (and ignoring the shape singleton) or vice versa. In other words, for the first 175 ms following stimulus delivery, neuronal activity was identical regardless of whether the stimulus matched the search goal or did not match the search goal. Similarly, salient items can modulate neuronal responses in subcortical regions, most notably in the superior colliculus (SC), a region strongly associated with the generation of saccadic eye movements (Boehnke & Munoz, 2008; Krauzlis, Lovejoy, & Zénon, 2013). Activity within the SC is sensitive to both stimulus-driven and top-down parameters. For example, when a peripheral cue is flashed just before onset of a visual target, saccadic latency to the target is reduced and the corresponding neuronal response in SC is larger. Importantly, this cueing benefit is larger when the cue is predictive of the target location, which suggests that the SC is not simply responsive to low-level feature differences within a scene (Fecteau, Bell, & Munoz, 2004).

The early influence of salience bears an electrophysiological marker, as well. A physically salient stimulus can lead to a lateralized positivity in the interval of the visual P1 and N1, known as the *positivity, posterior contralateral* (Ppc). The Ppc is elicited by both target and nontarget singletons, and is hypothesized to reflect a salience-driven signal that may bias subsequent selection. That the Ppc is elicited by both task relevant and task irrelevant stimuli further supports the idea that salience affects visual processing prior to the application of top-down attentional control.

The application of top-down attentional control appears to coincide with the emergence of the N2pc component, which typically emerges about 170—250 ms post stimulus. Some evidence exists, by way of the N2pc, for the (erroneous) capture of attention by a salient but irrelevant distractor. For example, Hickey et al. (2006) tracked the locus of selection in a mixed-feature ASP, in which the colors and forms of the target and nontargets changed unpredictably from one trial to the next. In that study, there was evidence for the early selection

of a highly salient color singleton distractor prior to the subsequent selection of the less salient shape singleton target. Similar results were observed in Hickey, Olivers, Meeter and Theeuwes (2011), which showed an early N2pc to a salient but irrelevant item. In a re-analysis of the data published initially in Hickey et al. (2006), Hickey, van Zoest and Theeuwes (2009) divided trials into quartiles by response speed and found that the distractor N2pc occurred earlier on the slowest trials. From this, the authors concluded that the fastest shifts of attention are directed towards the most salient item.

In other studies, the evidence for stimulus-driven capture is either ambiguous or absent outright. For example, a re-analysis of Hickey et al. (2006) revealed that the distractor-elicited N2pc—a critical piece of evidence supporting capture—was absent when the sample size was increased (McDonald et al., 2013). Similarly, there was no evidence for capture by the salient distractor in two variants of a fixed-feature search task, in which the properties of the target and the distractor remained static across all trials (Gaspar & McDonald, 2014; Jannati et al., 2013). However, an important detail emerges from these studies: whereas distractor capture is prevented on the fastest trials, on slow-response trials observers initially inspect the most salient (but irrelevant) item. Although these findings are technically inconsistent with the idea of capture—which posits that the most salient item will *always* be selected—they do reveal that salience-driven selection is probably nuanced.

A solution to these disparate results may lie in a recent study conducted by Gaspar and colleagues (Gaspar, Christie, Prime, Jolicœur, & McDonald, 2016). In that study, observers searched for a color singleton target while ignoring an even more salient color singleton distractor. Measures of visual short-term memory capacity (VSTM) were obtained from all participants and ERP waveforms were computed based on a tertile split of VSTM score. The results were striking: Whereas high-capacity observers effectively implemented a suppressive mechanism to prevent capture by the distractor, low-capacity observers showed a distractor-elicited N2pc, consistent with capture. In other words, some (but not all) observers can implement top-down guidance to prevent salience-driven automatic selection.

Taken together with the present results, two main conclusions can be drawn. First, in the absence of a top-down bias towards or away from a singleton, relative differences in the

perceived salience of each stimulus are sufficient to consistently bias the order of selection. This is consistent with both the theory that the item with the highest priority—defined as the combination of both salience and task relevance—wins the initial competition for selection. Second, top-down attentional parameters can vary the weightings attached to each item's salience, in order to promote the selection of one stimulus relative to another (Desimone & Duncan, 1995). One's ability to implement this mechanism likely varies both with stimulus-level parameters (e.g. fixed- versus mixed-feature search) and innate differences in VSTM capacity.

Chapter 4. The Timecourse of Attentional Deployment in Two-Target Visual Search

4.1. Abstract

A long-standing debate centers on whether visual attention selects only a single item at a discrete location within the visual field (serial selection) or can simultaneously select multiple items at different locations within the visual field (parallel selection). Here, an electrophysiological marker of attentional selection (N2pc) was used to track the deployment and timecourse of attention in three visual search experiments. In all studies, search displays contained four homogenous distractors and two singletons, one a highly salient color singleton and the other a less salient shape singleton. These stimuli had the effect of biasing the order of attentional selection such that search commenced at the color singleton, even when there was no strategic benefit to doing so. In the first experiment, the timecourse of the N2pc revealed that selection of the second item was initiated prior to the termination of selection of the first item—evidence for partially parallel attentional object selection. In the second experiment, the selection of the second item was delayed and selection was done discretely at each singleton, consistent with serial selection. In the third experiment, observers initially selected the less salient shape singleton, suggesting that salience can be overridden.

4.2. Introduction

Humans and other organisms move their eyes in sequential fashion to inspect different locations of the visual environment. According to most contemporary models of visual selection, attention can also be oriented in a serial fashion while the eyes remain fixed (that is, covertly). The precise nature and time course of these hypothetical serial shifts of attention has been debated for decades, and several challenging questions have been posed. Chapter 4 addresses four such questions: Does salience bias the order of selection? Can salience-driven biasing of selection be overridden? Can multiple items be selected at the same time or must

each item be selected in sequential fashion, and, if selection is sequential, how long does it take to redeploy attention from one item to another?

These questions have been investigated using the visual search paradigm, in which participants identify a target item in displays containing several nontarget distractors. In these conditions, many contemporary models of attention propose that item identification is accomplished by way of a two-stage processing stream like the one depicted in Figure 4-1. In an early “pre-attentive” stage of processing, basic visual features are processed in parallel and a retinotopic salience map is computed on the basis of local contrast and relevance (Bichot et al., 2005; Fecteau & Munoz, 2006; Laurent Itti & Koch, 2001; Wolfe, 2007). The salience map is then used to select an item or location for additional “attentive” processing, with stronger activations on the saliency map corresponding to a higher likelihood of selection. During the attentive stage of processing, multiple processing steps are required to locate an item (spatial selection), filter out other nearby items (spatial filtering), and to determine the identity of the attended item (identification). If the target has by far the strongest activation on the salience map, then it can be selected automatically and attentive processes are performed on it alone. This leads to so-called “pop out” search (often also called parallel search), in which the time to respond to the target remains the same regardless of the number of distractors in the display (Nakayama & Silverman, 1986). If however no item has a strong activation on the salience map, attentive-stage processes must be applied to multiple items within the field of view. In these search conditions the time to find and respond to the target increases with the number of distractors, typically by 10—50 msec per additional distractor (Wolfe, 1998).

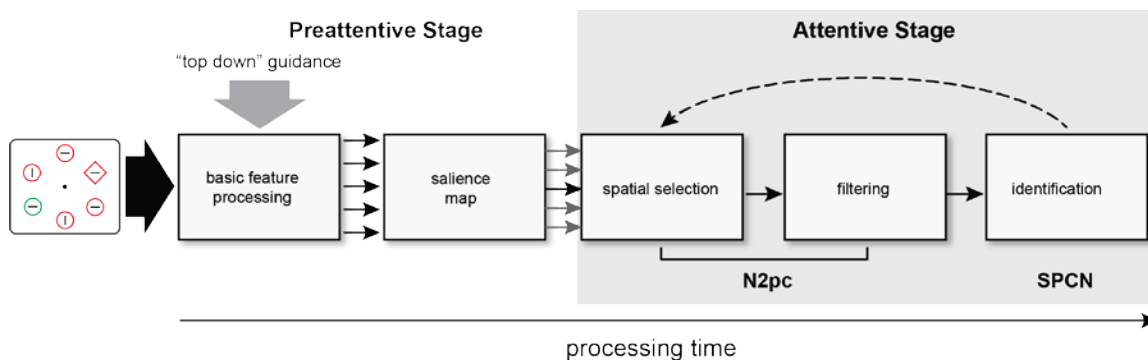


Figure 4-1. Hypothetical Sequence of cognitive processes during the inspection of scenes containing multiple possible targets.

To date, it remains unclear exactly how attentive processes are accomplished in these latter, *inefficient* search conditions. The issue has often been framed as a debate between serial and parallel modes of attentional item selection. According to the former account, attentive processes are restricted to a single item at any one time, as depicted by the single black arrow connecting the saliency map to spatial selection in Figure 4-1. If the attended item is identified as a nontarget, it is rejected and attention is deployed to another item in the display. This process is repeated until the target is found. According to the latter account, more than one item can be processed at the attentive stage, as depicted by the additional gray arrows connecting the saliency map and spatial selection. As with serial selection, this process repeats—albeit on multiple items at a time—until the target is found. Unfortunately, both the serial and the partially-parallel selection accounts make identical predictions on the associated behavioral visual search data—namely, that the amount of time required to find an inconspicuous target increases as a function of the number of nontargets in the display. As a result, it has been extremely difficult to rule out one explanation without simultaneously ruling out the other (see for e.g. Townsend, 1990).

There is converging behavioral and neurophysiological evidence that serial item selection occurs under certain conditions. For example, in a study by Theeuwes, Godijn and Pratt (2004), participants deployed attention to one of the four quadrants of a search display following the presentation of a symbolic spatial cue at fixation. After a variable SOA, participants were presented with a second symbolic cue within the cued quadrant that instructed them to attend a different quadrant. On half of trials, a target appeared at this second attended location;

on the other half of trials, a probe was presented briefly within one of the four quadrants, to which participants made a speeded button response. If the SOA was brief (< 250 msec), RTs were shorter when the probe appeared at the first cued location than when it appeared at the second cued location. By comparison, if the SOA was long (> 250 msec), RTs were shorter when the probe appeared at the second cued location. These findings suggest that attention is unavailable to process a stimulus at a new location until the stimulus at an initially selected location is identified fully. Furthermore, the results indicate that it takes at least 200 msec for attentive processes to identify one item and to shift serially to a new item.

Similarly, a series of experiments conducted by Woodman and Luck (1999, 2003) assessed the locus and timing of attentional selection using the N2pc component of the time-locked ERP. These experiments differed from standard visual search paradigms in that displays contained two potential target singletons presented among mostly homogenous nontargets. Observers had to carefully inspect these singletons for a target-defining feature (a gap on a designated side). The order of selection was biased in order to encourage the initial inspection of one of the two singletons (e.g. by placing one of the two singletons closer to central fixation). Discrete, non-overlapping N2pc responses emerged to each singleton, consistent with the serial selection and inspection of each item. Moreover, the speed of attentional redeployment was estimated based from the difference in the onset of each N2pc response, which in all experiments was approximately 100 msec. In other words, observers first inspected one singleton and, if it lacked the target-defining feature, shifted and selected the other singleton after about 100 milliseconds.

In other tasks, overlapping N2pc responses emerged to each singleton, consistent with the parallel selection and inspection of each item. In one such study, the N2pc was used to track the deployment of attention when two search displays were presented in rapid temporal succession (Eimer & Grubert, 2014). Each of these displays contained a target of a known color and a randomly colored distractor, and observers reported if the two targets were categorically similar (e.g. two numbers) or dissimilar (e.g. one number, one letter). The SOA of the two displays was manipulated between 10, 20, 50 and 100 msec, and the N2pc to each singleton was isolated by placing either the first or the second target on the vertical midline (midline items cannot elicit the N2pc). When the SOA was 100 msec, the difference in the onset of the second N2pc

relative to the first N2pc was also 100 msec. However, as the SOA was decreased the onset of the second N2pc perfectly mirrored the reduction in SOA. At the shortest, 10 msec SOA, the onset of the second N2pc lagged that of the first by 10 msec. This in turn led to overlapping N2pc responses to each target, consistent with parallel and independent deployment of attention to each target.

In a follow-up study (Grubert & Eimer, 2015), the N2pc was tracked to two singletons presented within the same search display. Here, displays contained two homogenous distractors, one target of a unique, fixed color, and one target of a unique, random color. All items were single-digit numbers and participants reported whether the value of the random-colored number was greater or smaller than that of the fixed-color number. As before, the N2pc to each singleton was isolated by placing one item in a lateral visual field and the other on the vertical midline. The N2pc was elicited first by the fixed-color target and subsequently by the random-color target, but here the onset difference of the two N2pc responses was about 60 msec. This again led to temporally overlapping N2pc responses to each target. These results suggest that attention selects items at different locations in a serial manner, but engages in subsequent attentive processes on these items in a parallel manner. This is consistent with other explanations for inefficient visual search, in which the visual system serially selects item for parallel object identification (cf. Wolfe, 2007).

Taken together, the extant results portray contrasting and inconsistent patterns of attentional object selection, with certain tasks eliciting relatively fast shifts of attention and other tasks relatively slow shifts of attention. Chapter 4 sought to determine whether task-related demands influence whether participants search in a primarily parallel or in a purely serial fashion. In studies with faster, overlapping object selection, observers made a coarse comparison of two items (Eimer & Grubert, 2014; Grubert & Eimer, 2015). For example, in Eimer and Grubert (2014), participants were presented two brief, unmasked displays, each of which contained two alphanumeric stimuli rendered in different colors. Participants were instructed to attend to stimuli of a particular color (e.g. red) and report whether their alphanumeric category was the same (e.g. both numbers) or different (e.g. one letter, one number). Here, two targets appeared on each and every trial and the task could not be performed if search was terminated after selecting just one target. By comparison, in studies with slower, non-

overlapping object selection, observers made a fine discrimination of two items. For example, in Woodman and Luck's (1999) study, participants selected specific-color (e.g. red) unfilled square singletons to determine if one of them was a target. The target differed from same-color nontargets based on a subtle local feature—namely, a 0.2° gap that was either on one of the sides (target) or on the top/bottom (nontargets). Thus, discrimination between target and nontargets would likely require close scrutiny. The initial selection was biased toward one of the potential target items, either by making one item closer to central fixation or by making the target more likely to appear in a singleton of a certain color. Here, search could be terminated if the initially selected item was deemed to be the target because the display contained at most one target.

To investigate this question, task response was manipulated in three, between-subject experiments. In all three experiments, observers searched displays that contained four homogeneously colored nontargets, one highly salient color singleton, and one less salient shape singleton. In the first experiment, observers compared the contents of both singletons and responded if the line segments contained within were oriented in the same or in different directions. By comparison, in the latter two experiments, observers searched for a line segment of a specific orientation (say, vertical) and reported if this item was present in either singleton. In the second experiment the target line segment was more likely to appear in the color singleton, and in the third experiment the target line segment was more likely to appear in the shape singleton. These paradigmatic differences lead to a key distinction between the first task and the latter two tasks. In the first task, a response can be generated only after both singletons are inspected, but it is not necessary to carefully inspect each singleton for a specific target-matching feature. In contrast, in the latter two tasks, a response can potentially be generated after inspecting one singleton, but it is necessary to carefully inspect that singleton for a specific target-defining feature. Because of these differences, there is no strategic benefit afforded in the first task by initially inspecting either singleton (cf. Chapter 3), whereas a strategic benefit is conferred in the latter experiments by initially inspecting the singleton most likely to contain the target.

4.3. Materials and Methods

The Research Ethics Board at Simon Fraser University approved the experimental procedures used in this chapter.

4.3.1. Experiment 4-1

Participants.

Thirty-three observers participated in Experiment 4-1 after providing informed consent. Data from four participants were excluded because accuracy was less than 70%, and data from four additional participants were excluded due to oculomotor activity. This left 26 participants in the grand average (mean age 21.0 years, 13 female, two left handed). All participants reported normal or corrected-to-normal vision and were screened for colorblindness using Ishihara color plates.

Apparatus.

Experiment 4-1 was conducted in a dimly lit, acoustically and electrically shielded chamber illuminated by DC-powered LED lighting. Participants sat 57 cm from a computer monitor operating at a resolution of 800 × 600 pixels and an 85 Hz vertical refresh. Stimulus presentation was controlled by Presentation (Neurobehavioral Systems Inc, Albany, CA) from a Windows-based computer. The EEG was recorded using custom software (Acquire) from a second Windows-based computer, using a 64-channel A-to-D board (PCI 6071e, National Instruments, Austin, TX) connected to a high input impedance EEG amplifier system (SA Instruments, San Diego, CA).

Stimuli and Procedure.

Prior to the commencement of the main experiment, participants subjectively matched the brightness of red to green, until the participant was satisfied that the two were isoluminant. The process was repeated four times, and the average red value used subsequently (Jannati et al., 2013).

Search displays contained six items (2.3° diameter) spaced equally around an imaginary circle (5.0° radius) centered on a fixation point. Two items were placed on the vertical meridian, one above and one below fixation. Four of the items were colored, unfilled circles rendered in the same color (e.g. red), a fifth item was an unfilled diamond rendered in the same color, and the sixth item was an unfilled circle rendered in a different color (e.g. green). Each item contained either a vertical or horizontal line segment ($2.27 \times 0.4^\circ$). The background of the display was black (0.03 cd/m^2), and the lines and fixation point were light gray (40.1 cd/m^2). Green items were always rendered with the same brightness (25.9 cd/m^2 , $u' = .27$, $v' = .61$), and red items were rendered with the brightness-matched value established prior to the start of the experiment. Colors were counterbalanced across participants. Each trial began with a fixation point displayed for 800–1200 ms, followed by the search display. The search display would remain visible for 4,000 ms or until a response was registered. Participants indicated, via a speeded button response, if the lines contained within the color singleton and shape singleton were oriented in the same or in different directions. In this way, performance would not be improved by reliably directing attention to one of the two singletons before the other (Fortier-Gauthier et al., 2012). Participants were instructed to not move their eyes from fixation to complete the task. Each block of 32 trials contained an equal number of trials in which the color singleton was presented in a lateral visual hemifield and the shape singleton on the vertical visual meridian (isolated color singleton), in which the shape singleton was presented in a lateral visual hemifield and the color singleton on the vertical visual meridian (isolated shape singleton), in which both singletons were presented in the same lateral visual hemifield (same-side), and in which the two singletons were in opposing visual hemifields (opposite-side trials). Trials were randomly shuffled by the experimental computer, and participants completed 32 blocks for a total of 1,024 trials.

Electrophysiological recording and analysis.

The continuous electroencephalogram was recorded at a 500 Hz sampling rate from Ag/AgCl electrodes mounted in an elastic cap (Sands Research, Inc.) from 24 scalp locations: FP1, FPz, FP2, F7, F3, Fz, F4, F8, T7, C3, Cz, C4, T8, P7, P3, Pz, P4, P8, PO7, POz, PO8, O1, Oz, and O2. An additional loose-lead electrode was attached to the left mastoid (M1). These electrodes were referenced to the right mastoid (M2) during recording and were re-referenced offline to

the average of both mastoids. The horizontal electrooculogram (HEOG) was recorded from bipolar Ag/AgCl electrodes positioned 1 cm lateral to the outer canthus of each eye. EEG and HEOG channels were amplified with a gain of 20,000 within a pass-band of 0.01–100 Hz and were digitized at 500 Hz. A semi-automatic procedure was performed to remove epochs of EEG that were contaminated by eye movements, blinks, and amplifier blocking. Artifact-free data were then used to create averaged ERP waveforms, which were digitally low-pass filtered (-3 dB cutoff at 30 Hz) to remove high-frequency activity. The averaged event-related HEOG did not exceed 2 μ V for any individual participant, indicating that gaze remained within 0.3° of the fixation point for most trials (McDonald & Ward, 1999).

ERPs were computed for each of the four stimulus configurations from correct-response trials, relative to a 100-ms pre-stimulus baseline. For each participant, the ERP waveforms were collapsed across left and right visual hemifields and left and right electrode sites to create waveforms recorded contralateral and ipsilateral to a lateral singleton. For the opposite-side condition, 'contralateral' and 'ipsilateral' were defined relative to the color singleton in all three experiments. Lateralized ERP difference waveforms were then derived for each condition by subtracting the ipsilateral waveform from the corresponding contralateral waveform using lateral occipital electrode sites (PO7 and PO8). Negative voltages were plotted upward such that the N2pc would appear as an upward deflection in these difference waveforms.

The presence (or absence) of the N2pc elicited by each singleton was ascertained by way of a signed area analysis. For each condition, the total negative area of the contralateral-minus-ipsilateral difference wave was measured from 180 to 380 ms. The negative area of an equally wide pre-stimulus baseline (noise) was then subtracted from this value to obtain a pure measure of the negative area of the N2pc. The mean amplitude of the N2pc elicited by the color singleton was measured from 200—300 ms and the mean amplitude of the N2pc to the shape singleton was measured from 300—400 ms. The onset and offset latencies each singleton was quantified using a jackknife method as the point at which the ERP difference waveform reached 33% of its peak negativity within a 75—400 ms post-stimulus interval.

Mean amplitudes and latencies were compared using mixed-model and repeated-measures ANOVAs. For the jackknife latency analyses, the resultant statistical values were

adjusted accordingly (Miller et al., 1998; Ulrich & Miller, 2001). In the interest of clarity, uncorrected degrees of freedom are reported. All post-hoc analyses were performed with Bonferroni correction for multiple comparisons.

4.3.2. Experiment 4-2

Participants.

Thirty-four new observers participated in Experiment 4-2 after giving informed consent. Data from nine participants were excluded from the analysis because >35% of the trials were rejected due to eye movements, blinking, or amplifier blocking, leaving 25 participants (mean age 20.7 years, 14 female, three left handed) in the grand average. All participants reported normal or corrected-to-normal vision and were screened for colorblindness using Ishihara color plates.

Apparatus.

The apparatus was identical to that used in Experiment 4-1.

Stimuli and Procedure.

The stimuli and procedures were identical to Experiment 4-1 except for the following changes. In Experiments 4-2, participants indicated, via a speeded response, the presence or absence of a line segment of a specific orientation (e.g. vertical) contained within either the color or shape singleton (but never both). This target line segment was present on 50% of trials, and the orientation of the target line was counterbalanced across participants. On target-present trials in Experiment 4-2, the target was located within the color singleton on 75% of trials and within the shape singleton on the remaining 25% of trials (referred to herein as the C75 task). Participants were informed of these probabilities at the outset of the experiment to minimize learning effects, but were otherwise not encouraged to initiate search at either of the two singletons.

Electrophysiological recording and analysis.

The electrophysiological recording and analysis were identical to Experiment 4-1.

4.3.3. Experiment 4-3

Participants.

Thirty-one new observers participated in Experiment 4-3 after giving informed consent. Data from eight participants were excluded from the analysis because >35% of the trials were rejected due to eye movements, blinking, or amplifier blocking, and one participant was excluded from the analysis due to poor task compliance. In total, this left 22 participants (mean age 20.5 years, five male, four left handed) in the grand average. All participants reported normal or corrected-to-normal vision and were screened for colorblindness using Ishihara color plates.

Apparatus.

The apparatus was identical to that used in Experiment 4-1.

Stimuli and Procedure.

The stimuli and procedures were very similar to Experiment 4-2 except for the following changes. In Experiments 4-3, participants again indicated, via a speeded response, the presence or absence of a line segment of a specific orientation (e.g. vertical) contained within either the color or shape singleton (but never both). This target line segment was again present on 50% of trials, and the orientation of the target line was counterbalanced across participants. On target-present trials in Experiment 4-3 however, the target was located within the shape singleton on 75% of trials and within the color singleton on the remaining 25% of trials (referred to herein as the S75 task). Participants were informed of these probabilities at the outset of the experiment to minimize learning effects, but were otherwise not encouraged to initiate search at either of the two singletons.

Electrophysiological recording and analysis.

The electrophysiological recording and analysis were identical to Experiment 4-1.

4.4. Results

In three between-subject experiments, observers searched displays that contained four homogeneously colored nontargets, one highly salient color singleton, and one less salient shape singleton. In the comparison task (Experiment 4-1), both singletons served as targets on every trial. Observers in that experiment compared the line segments contained within the two singletons and responded if the lines were oriented in the same or in different directions. In the C75 and S75 tasks (Experiments 4-2 and 4-3, respectively), observers responded to the presence or absence of a line segment of a specific orientation that was more likely to appear within one of the singletons. There were three experimental questions to address: (i) Does salience bias the order of attentional object selection in the absence of top-down control; (ii) Can top-down control prevent salience-driven capture; (iii) Do task requirements affect the timing of attentional object selection?

4.4.1. Behavioral results

Although the three tasks in Chapter 4 used identical stimuli, the nature of the response differed between experiments. The first behavioral analysis therefore sought to determine whether overall RT differed between the three tasks. Table 4-1 reports median RT and error rate for each display configuration for all tasks, after rejecting 14.4% (comparison task), 21.8% (C75 task) and 16.8% (S75 task) of trials that were contaminated by oculomotor artifact. RTs were collapsed across the four display configurations and across target presence/absence (for the C75 and S75 tasks). One-way ANOVAs revealed that RT did not vary significantly with task type, $F(2,70) = 1.10, p = .34$, but that accuracy did, $F(2,70) = 7.17, p = .002$, with post-hoc tests revealing that observers committed more errors in the S75 task relative to the other two experiments (Table 4-1).

Next, to determine if behavioral responses differed based on overt versus covert object inspection, speed and accuracy were compared between Experiment 4-1 (the comparison task) and the behavioral data from Experiment 3. Numerically, RTs were slower in Experiment 3 (1,328 ms) than in Experiment 4-1 (1,188 ms), however this effect was significant only at the one-tailed level, $t(43) = 1.94, p = .059$. Participants committed fewer errors in Experiment 3 (3.1%) than in

Experiment 4-1 (6.8%), $t(43) = 3.36, p = .002$. One possible explanation for these finds is that observers exchanged response speed for accuracy in Experiment 3 relative to Experiment 4-1. However, this pattern of results can also be explained by the fact that, relative to covert selection, overt object selection typically results in an enhanced perceptual image of the object and slower overall response times (Carrasco & McElree, 2001; Fairhall, Indovina, Driver, & Macaluso, 2009).

Next, the behavioural data were analyzed to determine if any performance or accuracy differences existed between the C75 and S75 tasks. Mixed-model ANOVAs were performed with two levels of the factor Task (C75, S75) and three levels of the factor Target Condition (target present in expected singleton, target present in unexpected singleton, target absent). As depicted in Table 4-1, RTs were fastest in both experiments if the target was presented within the expected singleton (i.e. within the color singleton in the C75 task; within the shape singleton in the S75 task) and slowest if the target was absent, as evidenced by a significant main effect of Target Condition, $F(2,90) = 126.3, p < .001$, but not of Task, $F(1,45) = 1.38, p = .25$. This suggests that observers commenced search at the singleton most likely to contain the target line segment, regardless of that item's salience. The pattern of RT results was also approximately similar between the C75 and S75 task, as evidenced by a non-significant interaction between Task and Target Condition, $F(2,90) = 0.73, p = .47$. In terms of accuracy, participants were more accurate in the C75 task, $F(2,90) = 238.5, p < .001$, and were less accurate when the target was presented within the unexpected singleton, $F(1,45) = 311.5, p < .001$. Accuracy on these trials was poorer in the S75 task than in the C75 task, which led to a significant Task x Target Condition interaction, $F(2,90) = 85.4, p < .001$. This suggests that in the S75 task, observers had difficulty shifting attention from the less-salient to the more-salient item, a finding loosely consistent with the idea of a serial, self-terminating (and slow) selection mechanism.

Finally, to determine if RT varied due to differences in the configuration of the two singletons, a repeated-measures ANOVA was performed for the four stimulus configurations in the comparison task. Response times varied significantly across the four stimulus configurations, $F(3,75) = 12.03, p < .001$, with responses being significantly slower in opposite-side trials relative to all other stimuli configurations.

Table 4-1. Median Correct Response Times (RTs) and Error Rates by Experimental Condition

Task / Stimulus Configuration	Median RT (SEM), Ms	Error rate (SEM), %
Experiment 4-1 (comparison task)		
Isolated color singleton	1186 (43.5)	7.8 (0.98)
Isolated shape singleton	1213 (40.5)	7.1 (1.04)
Opposite-side	1227 (45.8)	5.6 (0.82)
Same-side	1120 (44.2)	6.8 (0.89)
Experiment 4-2 (C75 task)		
Target in color singleton (expected)	911 (38.9)	4.8 (0.62)
Target in shape singleton (unexpected)	1239 (34.6)	10.0 (1.12)
Target absent	1254 (43.2)	3.4 (0.53)
Experiment 4-3 (S75 task)		
Target in shape singleton (expected)	883 (29.8)	2.8 (0.55)
Target in color singleton (unexpected)	1196 (40.9)	26.3 (1.68)
Target Absent	1263 (46.1)	2.8 (0.39)

4.4.2. Electrophysiological results

Salience biases the order of object selection in the absence of top-down attentional control.

The first two experimental questions were whether salience biases the order of attentional object selection in the absence of top-down control and whether top-down control can prevent salience-driven capture. To investigate these questions, the timecourse of attentional selection was isolated for each singleton by placing one item in a lateral visual field and the other on the visual midline. Figure 4-1 depicts ERP waveforms for each such isolated singleton; for the C75 and S75 tasks, these waveforms were computed from target-absent trials, during which observers would have had to select and inspect both singletons. For each condition, the total negative area of the contralateral-minus-ipsilateral difference wave was measured from 180 to 380 ms. The negative area of an equally wide pre-stimulus baseline (noise) was then subtracted from this value to obtain a pure measure of the negative area of the N2pc. This analysis revealed the first important finding regarding the effect of salience on object selection: the N2pc was elicited by all singletons except by the color singleton in the S75 task ($p = .32$, all other $p < .018$). For the remaining stimuli, the mean amplitude of the N2pc elicited by the color singleton was measured from 200—300 ms and the mean amplitude of the N2pc to the shape singleton was measured from 300—400 ms. The mean amplitude of the N2pc was significantly different from zero in all cases (all $p < .044$), the amplitude of the color N2pc did not differ between the comparison and the C75 task, $t(49) = 1.07$, $p = .29$, and the amplitude of the shape N2pc did not differ between the three tasks, $F(2,70) = 1.80$, $p = .17$. Collectively, this demonstrates that observers inspected all singletons within the typical N2pc time interval (approx. 170—350 ms), except for the color singleton in the S75 task.

To determine the timing of attentional object selection, the onset latencies of the color and shape N2pc components were measured in the comparison task and the C75 task (the S75 task was not analyzed at this stage because the color singleton failed to elicit an N2pc). The onset latency was measured for each singleton as the point at which the ERP difference waveform reached 33% of its peak negativity within the 75—400 ms post-stimulus interval (Figure 4-2b). These latencies were then quantified using a 2 (Task) X 2 (Singleton Type) mixed-model ANOVA. The more salient color singleton was selected initially, as evidenced by a

significant main effect of Singleton Type, $F_{\text{corrected}}(1,49) = 22.7, p < .001$. Although the selection of the color singleton was later numerically in the comparison task (228 ms) than in the C75 task (201 ms), this difference was not found to be significant $p_{\text{corrected}} = .37$. In response then to the first two questions asked above, the results mirror those from Chapter 3 and further support the idea that salience “wins out” when several task-relevant items, of differing salience, must be selected for inspection. Specifically, in the comparison task the onset of the N2pc to the color singleton occurred about 35 ms before the onset of the N2pc to the shape singleton. However, the absence of the N2pc to the color singleton in the S75 task suggests that it is possible to override this salience-driven biasing of selection.

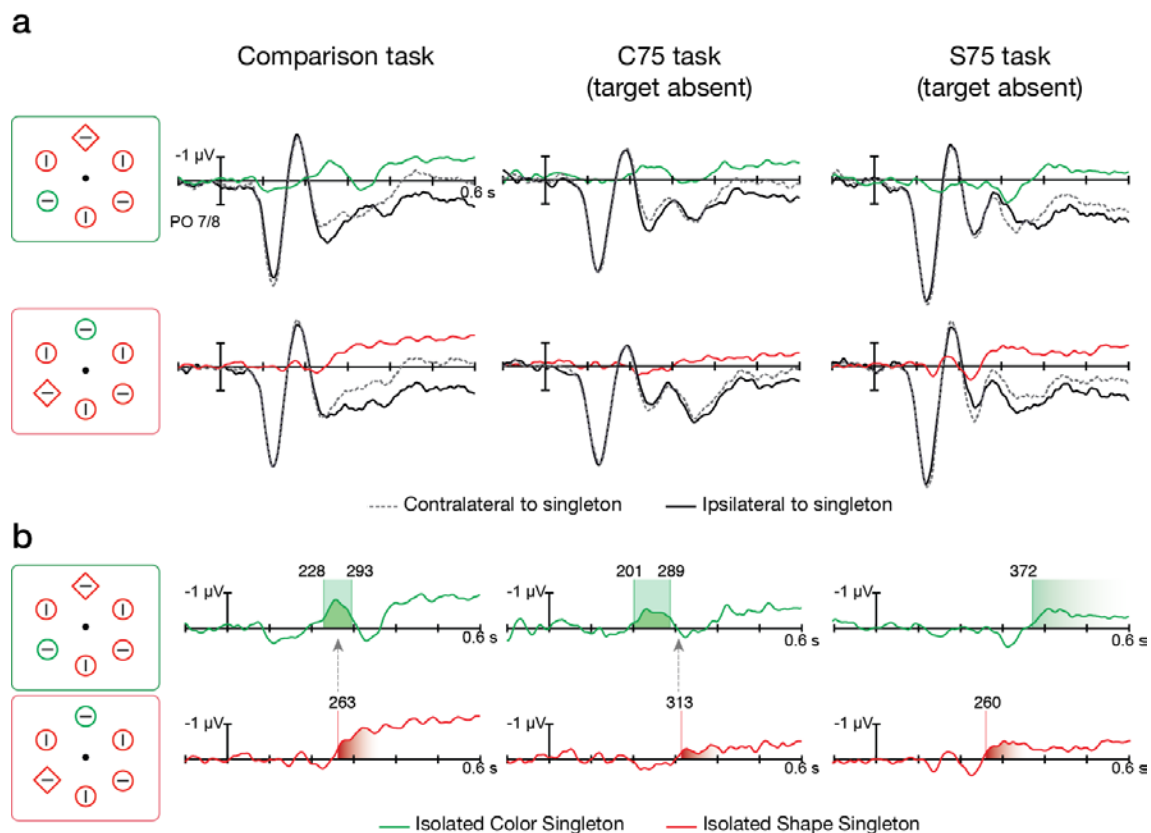


Figure 4-2. Stimulus configurations and ERP results for the comparison (Experiments 4-1), C75 (Experiment 4-2) and S75 (Experiment 4-3) tasks. (a) ERP waveforms recorded electrodes positioned ipsilateral and contralateral to each singleton, and contralateral-minus-ipsilateral difference waveforms. For the C75 and S75 tasks, the figures depict ERP waveforms recorded from target-absent trials. Top row: ERP waveforms for the isolated color singleton. Bottom row: ERP waveforms for the isolated shape singleton. (b) Contralateral-minus-ipsilateral difference waveforms for the two color singletons from (a), re-plotted for clarity. Shaded regions denote the N2pc to each singleton, and onsets and offsets are denoted above the abscissa.

Serial vs. parallel attentional object selection.

The third experimental question was whether task requirements affect the timing of attentional object selection. To answer this question, isolated N2pc onset latencies for each singleton were combined with similar measures for N2pc offset latencies—specifically, the point at which each ERP difference waveform diminished to 33% of its peak amplitude within 75—400 ms.

To explore the timing of the selection of the less salient shape singleton, the onset latency of the shape N2pc was assessed using a univariate ANOVA with three levels of the factor Task. This analysis confirmed that the onset of the N2pc differed significantly between the three Tasks, $F(2,71) = 9.73$, $p < .001$, and post-hoc comparisons revealed that the onset of the shape N2pc was significantly later for the C75 task (313 ms) relative to the other two conditions (both $p < .001$). In other words, participants were slowest to select the less salient shape singleton when they scrutinized the color singleton initially.

To determine if observers selected multiple items for simultaneous inspection, the offset of the color N2pc was compared against the onset of the subsequent shape N2pc in the comparison and C75 tasks. If object selection was partially parallel in the comparison task, this would be evidenced by the onset of an N2pc to the shape singleton preceding the offset of the N2pc to the color singleton. To investigate this, N2pc latency measures were analyzed using a 2 (Task) x 2 (Measure; color N2pc offset latency, shape N2pc onset latency) mixed-model ANOVA. There was no overall main effect of Task [$F(1,49) = 2.49$, $p = .121$] or Measure [$F(1,49) = 0.29$, $p = .59$], but there was a significant crossover interaction between these two factors, $F(1,49) = 5.84$, $p = .019$. The nature of this interaction is highlighted by the dashed gray arrows in Figure 4-2b:

whereas the onset of the shape N2pc occurred after the offset of the color N2pc in the C75 task, in the comparison task the onset of the shape N2pc instead occurred before the offset of the color N2pc. This suggests that each singleton was selected discretely in the C75 task, which has been attributed to serial object inspection (Woodman & Luck, 1999, 2003). In contrast, in the comparison task, the selection of the shape singleton occurred significantly earlier than the offset of the color singleton, a finding that has been attributed to parallel object inspection (Eimer & Grubert, 2014; Grubert & Eimer, 2015).

In response then to the third experimental question, these results suggest that the timing of subsequent item selection—but not the timing of initial item selection—can be affected by the nature of the response required, with careful scrutiny for a target-defining feature leading to slower, serial shifts of attention from one item to another.

Salience-driven suppression facilitates the immediate selection of less-salient objects.

The ERP difference waveforms elicited by the color singleton became positive from about 300-350 ms post stimulus (top rows of Figure 4-1a and 4-1b). Similar lateralized positivities have been observed in a number of recent visual search experiments (Fortier-Gauthier et al., 2012; Hilimire, Mounts, Parks, & Corballis, 2009, 2010; Leblanc, Prime, & Jolicoeur, 2007), and may reflect either the individuation of the target (Hilimire, Mounts, Parks, & Corballis, 2011) or a suppression-based termination of target processing (Sawaki, Geng, & Luck, 2012). To ascertain the presence of this lateral positivity, the mean amplitude of the contralateral-minus-ipsilateral waveform was measured from 300-350 ms for all three experiments. This positivity was not found to be significant in either the comparison task or the C75 task (all $p > .52$), but was significant in the S75 task, $t(21) = 3.43$, $p = .003$. This result is somewhat surprising, given that the lateralized positivity occurred without a preceding N2pc and thus without evidence for the selection of the color singleton. This is inconsistent with both the target individuation and attentional termination accounts. Instead, this positivity may reflect the active, temporary suppression of the more salient color singleton, in order to promote the selection of the less salient shape singleton. This is broadly consistent with a lateralized ERP effect known as the distractor positivity (P_D ; Hickey, Di Lollo, et al., 2009). The P_D is often elicited by the most salient item if that item is a distractor and the second-most salient item the target (Gaspar et al., 2016;

Gaspar & McDonald, 2014). Thus far, the P_D has not been observed when the most salient item is potentially a target, as in the S75 task. To further investigate, the mean amplitude of this putative P_D was measured on isolated color singleton trials in which the target was present within the shape singleton. On these trials, observers should initially select the shape singleton, detect the target line segment, and therefore should not select the color singleton. The P_D was again significantly different from zero, $t(21) = 4.55, p < .001$, and its mean amplitude was not found to differ from that on target-absent trials, $t(21) = 0.33, p = .74$. Taken together, the results suggest that, (i) observers implemented a suppressive mechanism to override salience when initially selecting the second-most salient item, and (ii) did not disengage this suppressive mechanism within the typical N2pc time interval, even when required to shift attention towards this most salient item.

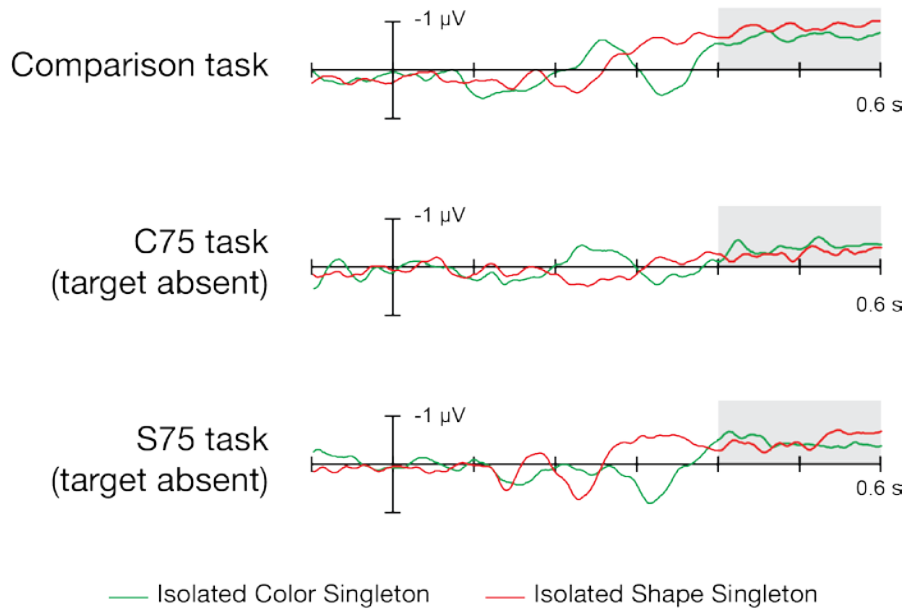
Selection, but not salience, affects the transfer of information into working memory.

Following the N2pc, a late negativity was evident in the ERP waveforms for many of the isolated singleton displays. This component, the sustained posterior contralateral negativity (SPCN), is thought to reflect the transfer of information into working memory (Corriveau et al., 2012; Jolicœur, Brisson, & Robitaille, 2008; Luria, Sessa, Gotler, Jolicœur, & Dell'Acqua, 2009; Vogel & Machizawa, 2004). There were two questions to address here: does the SPCN vary in amplitude with target salience, and does it scale in amplitude linearly with the number of attended items?

The first question was investigated by measuring the amplitude of the SPCN to each singleton in all three tasks. For the C75 and S75 tasks, this was done by measuring the SPCN on target-absent trials, as those trials would require the selection and inspection of both items. These amplitudes were then analyzed using a mixed-model ANOVA with two levels of the factor Stimulus (color singleton, shape singleton) and three levels of the factor Task (comparison, C75, S75). These ERP waveforms are depicted in Figure 4-2a. The SPCN was significantly different from zero in all cases (all $t < 2.35, p > .029$). Moreover, the SPCN was approximately equal in amplitude in all conditions, as evidenced by a non-significant effect of both Stimulus Type, $F(1,70) = 0.90, p = .35$, and Task, $F(2,70) = 0.60, p = .55$. Next, the SPCN was measured on trials in which the two singletons were located in either opposing visual hemifields or in the same

hemifield. In the former stimulus configuration, the SPCN was not significantly different from zero in any task (all $t < 1.15$, $p > .26$). In the latter stimulus configuration, the amplitude of each isolated SPCN was subtracted from the measured mean amplitude; after this subtraction, the SPCN was also not significantly different from zero (all $t < 1.28$, $p > .22$). Thus, the SPCN is of approximately equal amplitude for both singletons; the SPCN scales linearly in amplitude when the two items are in the same visual field and is nullified when the two items are in opposite visual fields.

a



b

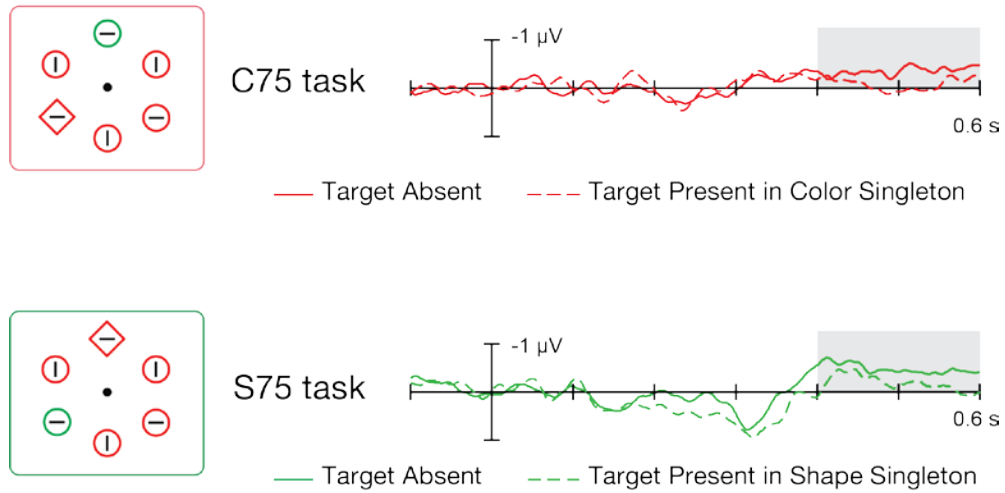


Figure 4-3. Contralateral-minus-ipsilateral difference waveforms from electrodes PO7/8 depicting SPCN amplitude. (A) SPCN amplitude for the isolated color singleton (red) and isolated shape singleton (green) in each task. (B) SPCN amplitude when the target was selected for inspection (solid trace) or not selected for inspection (dashed trace).

Next, the SPCN was compared between trials in which an object either was or was not selected for inspection, as depicted in Figure 4-2b. This was done for the C75 task by measuring the SPCN on isolated shape singleton trials and comparing the mean amplitude when the target was either present in the color singleton (shape singleton not selected for inspection) or absent (shape singleton selected for inspection). Similarly, this was done for the S75 task by measuring the SPCN on isolated color singleton trials and comparing the mean amplitude when the target was either present in the shape singleton or absent. In the C75 task the SPCN to the shape singleton was significantly different from zero on target-absent trials, $t(24) = 2.86, p = .009$ and was not significantly different on target-present trials, $t(24) = 0.68, p = .50$. Similarly, in the S75 task the SPCN to the color singleton was significantly different from zero on target-absent trials, $t(21) = 2.35, p = .029$ and was not significantly different on target-present trials, $t(21) = 1.72, p = .10$.

Collectively, the results reveal two important findings about the SPCN. First, the SPCN is insensitive to both physical salience and task response type, being equal in amplitude to both singletons and in all tasks. Second, the SPCN is linked to the selection of an object, and not by the presence of a potentially task-relevant object. This confirms that if the target line segment was identified in the more likely singleton, the other item is not necessarily processed automatically.

4.5. Discussion

Chapter 4 sought to address four fundamental questions pertaining to the neuro-electric mechanisms of attentional object selection. The first of these was whether salience biases the order of selection when several items must be selected and inspected, a question first investigated in Chapter 3. Mirroring the results from that chapter, Experiment 4-1 revealed that observers would initially select a more salient color singleton than a less salient shape singleton, even when no strategic benefit is afforded by doing so. This suggests that, in the absence of top-down guidance, the order of attentional object selection is profoundly biased by salience. However, when guidance was implemented in Experiment 4-3, by making a target-defining feature more likely to appear within a less salient shape singleton than a more salient color

singleton, observers could voluntarily select the shape singleton for initial inspection. This finding cannot be reconciled with the theory of salience-driven capture, which holds that observers initially select the most salient item within view, regardless of that item's relevance. Instead, it appears that the attentional priority of items can be flexibly configured based on a combination of their salience and their task relevance (Fecteau & Munoz, 2006).

In tandem with this first question, an additional question was whether—and how—individuals could prevent salience-driven selection. Two prominent hypotheses have been advanced to account for this ability: dimensional weighting and salience-driven suppression. According to the dimensional weighting hypothesis, the salience of certain items can be enhanced pre-attentively depending on the currently relevant visual feature dimension (Found & Müller, 1996; Müller, Reimann, & Krummenacher, 2003). In the current example, observers would boost the priority of any singleton defined within the relevant feature dimension (namely, a unique form). By comparison, according to the salience-driven suppression hypothesis, observers suppress salient but irrelevant items when searching for a known target (Jannati et al., 2013; Kumada & Humphreys, 2002; Sawaki et al., 2012). Although both hypotheses account for why the shape singleton was initially selected in this cross-dimension search task, the presence of the P_D to the color singleton lends more support to salience-driven suppression than to dimensional weighting. This account is also consistent with several other recent ERP studies which have linked the P_D with salience-driven suppression and the prevention of capture (Gaspar et al., 2016; Jannati et al., 2013, 2013; McDonald et al., 2013; Schubö, 2008; Töllner, Müller, & Zehetleitner, 2012). Indeed, the N2pc results from Experiment 4-3 add an important extension to those studies. To date, salience-driven suppression has been reported in tasks in which observers knew that the most salient item was *never* task relevant. Because of this, they could implement a strict attentional template to always ignore the most salient item. Such a template would be impractical in Experiment 4-3 because the color singleton nevertheless had to be selected and inspected on most trials.

Somewhat unexpectedly, there was no evidence for the suppression of the color singleton following its initial selection in Experiments 4-1 and 4-2. Such positivities have been reported in some visual search studies (Hilimire et al., 2009, 2010) and are thought to reflect the termination of attentional processes (Sawaki et al., 2012). In this view, it may be that the

suppression of the initially-selected item was not done in the present experiments because of the need to rapidly shift attention to a new item. Further studies will be necessary to ascertain this.

The third and fourth questions relate to the ability to select more than one item during visual search, and the timecourse for attentional selection of each item. In measuring the N2pc component of the time-locked ERP, different studies have observed different patterns of attentional object selection. For example, if observers are asked to carefully inspect two singletons for a task-defining feature, each object is selected discretely (Woodman & Luck, 1999, 2003). This is consistent with serial theories of selection, which hold that fine perception is restricted to a single item at a single location in the visual field. In contrast, if observers are asked to compare two items, both objects are selected at nearly the same time (Eimer & Grubert, 2014; Grubert & Eimer, 2015, 2016; Jenkins, Grubert, & Eimer, 2016). This is consistent with parallel—or partially parallel—theories of selection, which hold that fine perception can be divided across several items at different locations in the visual field.

Here, the number of objects selected for inspection varied with the nature of the response required. Specifically, object selection was done discretely when careful inspection was required, such that visual selection was performed exclusively for one singleton and not the other. In contrast, when a comparative evaluation was required of the two targets, selection operated as a hybrid of serial and parallel object inspection. It may be that parallel object selection and identification cannot be done in conditions when items differ in attentional priority (Fecteau & Munoz, 2006). By comparison, parallel (or partially parallel) selection may be possible when items are approximately matched for priority, albeit with individual selection and subsequent parallel identification. This is entirely consistent with the hybrid selection model that lies at the heart of Guided Search 4.0 (Wolfe, 2007).

Beyond these main results, three additional findings merit consideration. First, attentional object reselection was relatively fast in the comparison task, even though the singletons were defined in different visual dimensions (specifically, color and form). This finding is somewhat surprising in light of the dimensional weighting account, which holds that top-down attentional control can up-weight a particular visual dimension (e.g. color) at the level of

pre-attentive processing (Found & Müller, 1996). In theory, this would permit faster redeployments of attention if two singletons were defined within the same visual dimension than in different dimensions. Consistent with this idea, previous studies that have shown fast, partially-parallel shifts of attentional object selection (e.g. Eimer & Grubert, 2014) have done so with tasks in which both targets were defined by the same color. In the present study, partially parallel shifts of attention were also observed, even though the two singletons were defined in different visual dimensions. It remains to be systematically tested whether shifts of attention from one singleton to another can be accomplished as fast across visual dimensions as within them.

Second, the time at which attention selected the most salient item—the color singleton—was invariant between Experiments 4-1 and 4-2. In contrast, in Experiment 4-3 there was no evidence for selection of the color singleton within the typical N2pc time interval (approx. 170—250 ms). Similarly, the timing of the selection of the less salient shape singleton did not vary between Experiments 4-1 and 4-3 but was delayed in Experiment 4-2. Collectively, this suggests that there is a fixed, minimum amount of time necessary to complete pre-attentive processes before an item is available for selection, the duration of which varies with relative differences in the salience of the various items within view. Similar results have been reported by others, albeit indirectly by comparing response RTs with the latency of the N2pc (Töllner, Zehetleitner, Gramann, & Müller, 2011). Across the three experiments in this chapter, the onset of attentional selection could be delayed for both singletons but could not be promoted below a minimum threshold. Although it remains to be tested under more rigorous conditions, it appears that pre-attentive operations on the second-most salient item take approximately 35 additional milliseconds to complete relative to the most salient item.

Third, the amplitude of a late component, the SPCN, did not vary in amplitude either with singleton salience or task type. This component has been linked to the transfer of attended information into visual working memory (Corriveau et al., 2012; Jolicœur et al., 2008; Luria et al., 2009), and given that the amplitude of the SPCN scales linearly with the number of remembered items (Vogel & Machizawa, 2004; Vogel, McCollough, & Machizawa, 2005), this finding suggests that both singletons were represented equally in memory. Typically, the SPCN is collapsed across different stimuli, which obscures the relationship between SPCN amplitude and

underlying differences in stimulus salience. Some, however, have investigated how the SPCN changes as a function of target salience. However, in Jannati et al. (2013), separate groups of observers either searched for a color singleton (while ignoring a less salient shape singleton distractor) or searched for a shape singleton (while ignoring a more salient color singleton). No between-groups differences were observed in the amplitude of the target-elicited SPCN. Moreover, there was no evidence for an SPCN by the irrelevant distractor. This finding dovetails with the SPCN results from Chapter 4 and further supports the idea that task relevance, and not stimulus salience, affects the amplitude of the SPCN.

In conclusion, the results from Chapter 4 build atop those from the previous chapter. Experiment 4-1 confirmed that the order of attentional object selection is fundamentally biased by salience in the absence of top-down guidance. From there, Chapter 4 presents two new findings. First, the effect of salience on the order of object selection can be overridden, such that the second most salient item can be selected first. Second, the timing of attentional redeployment from one object to another varies as a function of task set, with object comparison permitting faster redeployments of attention compared to object discrimination.

Chapter 5. General Discussion

5.1. The Effects of Salience on Attentional Object Processing

This thesis investigated how exogenous and endogenous factors influence selective object identification. The topic is an old one: For example, Egeth, Jonides and Wall (1972) reported that targets that were largely dissimilar from distractors could be rapidly and accurately located, and that the time to find such a target was unaffected by the number of nontargets in the search display—an ability defined previously in this thesis as efficient search. On the basis of this efficient search, early studies argued that target detection could be accomplished by an array of parallel channels, each of which was independently capable of yielding a “target-present” output. In other cases, the time to respond to a target was found to increase with the amount of information that had to be processed. For example, in Sternberg (1966), participants compared a probe stimulus against a list of items retained in memory. Response times increased linearly with the number of memorized items. Similarly, Neisser (1967) showed that the time to find a particular letter of the English alphabet (say, ‘K’) increased with the number of letters appearing within a block of letters—that is, search was inefficient. On the basis of this inefficient search, it was argued that target detection was instead mediated by a mechanism that was fundamentally constrained to processing and identifying a single object at any one time.

These findings, of efficient and inefficient visual search, were consolidated within Treisman and Gelade’s (1980) highly influential feature integration theory (FIT). According to this account, efficient search occurs when the representation of just a single item—the target—emerges from a pre-attentively generated salience map. Inefficient search occurs when there is no single representation at the level of the salience map; here, FIT presumes that attention must be deployed serially to locations in the display to find the target. Subsequent ideas have expanded on FIT to propose that top-down goals can modulate salience-derived signals. This ability is central to many contemporary theories of visual attention, including Guided Search (Wolfe, 2007), Dimensional Weighting (Found & Müller, 1996), Theory of Visual Attention (Bundesen, 1990), Feature-Based Attention (Serences & Boynton, 2007), Attentional

Engagement Theory (Duncan & Humphreys, 1989) and Biased Competition (Desimone & Duncan, 1995).

Here, the effects of salience and guidance were studied in three chapters of experimental research. In Chapter 2, observers located a target defined by one of two possible colors, which was presented in displays that contained a varying number of heterogeneously colored distractors. Stimulus salience was broadly equated and the target could only be located by up-weighting two particular color attributes, corresponding to each of the two possible target colors. RTs increased linearly with display set size, a finding that has been interpreted to reflect the serial selection of each item in the display. Disconfirming this interpretation however, the target N2pc was elicited at the same time regardless of set size. Search inefficiency was instead ascribed to the time required to resolve the identity of the target, as evidenced by the fact that the duration of the N2pc—but not its onset latency—increased with set size. In Chapter 3, observers made a comparison of two targets that differed in relative salience. There was no inherent benefit to initially inspecting either item, and in the absence of top-down guidance the order of selection was strongly biased by salience. Finally, Chapter 4 used a modified version of the search task used in Chapter 3. When observers were required to identify a specific target feature within one of the two singletons—as opposed to comparing the two singletons against each other, as in Chapter 3—they were slower to select the second target. If the target was more likely to appear in the less salient singleton, observers could override salience and initially select and inspect the less salient item.

On the basis of these results, three ideas merit further discussion and consideration as they relate to salience and its impact on object selection and identification. The first is the observation that, in the absence of goal-driven selection, the order of selection is profoundly biased by salience. The search task used in Chapter 3 and in the first experiment of Chapter 4 was designed such that the two singletons would both have to be inspected before a correct response could be generated. Observers routinely selected the more salient of two singletons first, even though no performance benefit was afforded by doing so. Although it was not the primary research focus of this thesis, it is worth considering this result in light of the long-standing debate surrounding stimulus-driven automatic capture of attention. According to this theory, the most salient item within view will always “win” the competition for subsequent

attentional selection and processing. This capture cannot be prevented by top-down volitional goals, as the application of attention is slow and cannot override the innate bias conferred by salience at early stages of visual processing (Theeuwes, 1991, 1992, 2010). As a result, top-down guidance can only intervene and shift attention towards a relevant stimulus following capture.

There is merit to the theory of salience-driven capture. From an evolutionary perspective, the ability to process threatening stimuli in a rapid and automatic fashion would convey a clear survival advantage. Accordingly, differences in relative salience are known to affect stimulus processing in many areas of the cortex, including area V4, the posterior parietal cortex, and the frontal eye fields. Typically, salience emerges from a relative increase in neuronal firing rates within a particular region of neural tissue. For example, Buschman and Miller (2007) measured neuronal activity levels from neurons in both the frontal and the parietal lobes of monkeys as they performed an efficient and an inefficient visual search task. Firing rates from neurons in lateral intraparietal cortex were higher following the presentation of the more salient target in the efficient search task. Similarly, Lamme and colleagues (Lamme, 1995; Lamme, Rodriguez-Rodriguez, & Spekreijse, 1999) recorded activity levels from V1 neurons to diagonally oriented noise textures. Activity levels increased approximately 100 ms post-stimulus if a region was made more salient because of a global discontinuity (specifically, if the noise texture beyond the receptive field was rotated 90 perpendicular), and these enhanced levels of activation persisted for at least 400 ms through the recording interval.

Salient but irrelevant items also have well known consequences on behavioral responses during visual search. Relative to trials that contain either homogenous nontargets or a distractor of lesser nominal salience than the target, trials that contain a distractor of greater nominal salience result in longer response times (RTs) to the target (Theeuwes, 1991, 1992). This effect persists even when the identities of all the items—target, nontargets and salient distractor—remain fully fixed across all trials in an experimental session (Theeuwes, 1992). Similarly, when observers are permitted to overtly inspect the target during visual search, the salient distractor biases the trajectory of the saccade, either towards or away from its location (as introduced in Chapter 3).

Does this, however, mean that the most salient item will always capture attention? For example, the theory of salience-driven attention capture holds that the initial selection will always be for the most salient item within the field of view; if this item is task irrelevant then attention must disengage from that item and shift, based on an observer's goals, to the appropriate item. However, this idea is incompatible with the pattern of results observed in the third experiment of Chapter 4 (i.e. the S75 task). In that task, observers overrode salience and initially selected the shape singleton, as doing so was more advantageous than initially selecting the more salient color singleton. This finding is entirely consistent with many recent electrophysiological studies that have investigated this question of salience-driven capture. Specifically, although there is often an *RT interference penalty* associated with the presence of a highly salient distractor, the evidence for the automatic selection of a distractor is equivocal. On the one hand, some individuals may be more susceptible to salience-driven capture (Gaspar et al., 2016), and salience-driven capture may occur more often in mixed-feature search, in which the identities of the target and distractors vary unpredictably from one trial to the next (McDonald et al., 2013). On the other hand, it appears that individuals can, at least in some conditions, implement a suppressive mechanism that overrides salience and prevents the automatic selection of the most salient item (Eimer & Kiss, 2010; Kiss, Grubert, Petersen, & Eimer, 2011).

The N2pc results from Chapter 4 reveal an additional problem with this theory of obligate, salience-driven attentional capture. According to this idea, selective visual enhancement is restricted to a single item at any one time; if that item is not task relevant then attention must be redeployed serially to another item. It is now clear, however, that the visual system can enhance the representations of several items in tandem, and that it is not necessary to fully identify the most salient item before selecting another item. Although it is probably still the case that salience confers a temporal advantage, such that the most salient item is selected first, it is increasingly unlikely that object enhancement requires the serial selection assumed by salience-driven capture.

The second idea meriting further discussion and consideration is that salience is not derived exclusively from bottom-up contrast differences in a visual scene, and can instead be created based on flexible task parameters. On this basis, direct selection—that is, the ability to

selectively enhance a single item—can be implemented based on both exogenous and endogenous factors. In Chapter 2, observers were able to automatically select the target, even though it was no more conspicuous than the distractors. Likewise, in the S75 task of Chapter 4, observers were able to initially select the less salient shape singleton to determine whether it contained a target feature. Collectively, these results suggest that top-down attentional control is able to bias object selection based on a particular feature, possibly as early as at the generation of the salience map (see Figure 1-1). In other words, selection parameters can encode certain stimuli at a higher level within a selection queue, even when physical salience competes against this selection (Fecteau & Munoz, 2006).

These results are also consistent with findings from the contingent-capture cueing paradigm. In these tasks, observers search for a target defined by a particular feature (e.g. red) while ignoring a preceding cue display containing task-irrelevant, non-predictive items. A key finding from this paradigm is that RTs to the target are slower if one of the cue items is rendered with the same target-defining feature and presented at a different location to the subsequent target (Eimer & Kiss, 2008; Folk & Remington, 1998; Folk, Remington, & Johnston, 1992). Recently, it has been confirmed that this contingent capture by the nontarget cue item persists even if that item is not salient—that is, if it does not capture attention based on its bottom-up properties (Hopfinger & Ries, 2005). For example, in a recent study by Livingstone and colleagues (Livingstone, Christie, Wright, & McDonald, *In Press*; cf. Sawaki & Luck, 2013), observers performed a compound search task in which displays contained four differently-colored items, one of which was presented in a task-relevant color. Participants were briefly shown a cue display prior to this search array, in which items were task-irrelevant shapes but rendered from the same four palettes of colors. There was an N2pc elicited by the (irrelevant) cue item that matched the color of the to-be-found target. Collectively, these results highlight that direct attentional selection—including erroneous attentional selection—can be configured flexibly to permit the selective enhancement of features that are not physically salient on the basis of local contrast differences.

The third and final idea is that the timing of attentional object processing varies with salience and task requirements. It is now clear that the availability of an object for attentional enhancement—and, by association, the point at which an object emerges from pre-attentive

processing—is affected by relative differences in the salience of the to-be-selected item. Evidence in support of this comes from several sources. In Chapter 4, the latency of the N2pc was shorter to the more salient singleton in the C75 task (when a target feature was more likely to appear within the color singleton) than the less salient shape singleton in the S75 task (when a target feature was more likely to appear within the shape singleton). Importantly, the task requirements in both experiments were identical with the exception that one singleton was more likely to contain the target than the other. Given that all other aspects of the search display were identical, it must be concluded that less-salient items cannot be selected as rapidly as more-salient items. In the context of the theoretical framework outlined in Figure 2-1, this means that less-salient items take longer to emerge from pre-attentive processing.

Similarly, a study by Jannati et al. (2013) tracked the N2pc while participants searched either for a shape singleton while ignoring a more salient color singleton distractor, or for a color singleton while ignoring a less salient shape singleton distractor. The N2pc was earlier when participants searched for the color singleton and this latency difference existed even on distractor-absent trials. Similar results were observed in Töllner et al. (2011), in which the onset latency of the N2pc was tracked in a search task in which observers searched for either a color or an orientation singleton of varying salience. Relative to displays with a low-salience target, the presence of a high-salient target elicited both an earlier and a larger N2pc. Collectively, this again suggests that timing differences in the duration of pre-attentive processing are linked to the salience of the target and not to the salience of the distractor.

The results from Chapter 2 present an interesting counterpoint to this account. In Experiment 2-2, the onset of the N2pc was unaffected by the nontarget items, being of identical latency for both heterogeneously- and homogeneously-colored nontargets. On the one hand, this seems to be at odds with previous results: the salience of the target was presumably enhanced in the latter case, which should have resulted in an earlier N2pc. On the other hand, it is consistent with one of the main conclusions from that chapter—namely, that targets defined by a known color “pop out” at the level of pre-attentive processing. Given this, it may be that items defined by a known color can always be processed faster pre-attentively than items defined by other singleton properties, such as form. Additional studies will be required to test this hypothesis.

It may also be the case that the duration of pre-attentive processing is affected by top-down attentional parameters. This is best illustrated by comparing the latency of the shape N2pc between the S75 task of this thesis and Experiment 1 of Jannati et al. (2013). In the latter experiment, the N2pc reached its peak amplitude by approximately 250 ms; by comparison, in the former experiment the N2pc had only begun to emerge by that point. A possible explanation for these discrepant latencies may lie in the fact that the color singleton was never task relevant in Experiment 1 of Jannati et al. (2013), but was task relevant on the majority of trials in the S75 task. As a result, observers could not complete the latter task by inhibiting or suppressing the other singleton pre-attentively. By comparison, observers in Experiment 1 of Jannati et al. (2013) would have been able to ignore the color singleton at all times. Many theories predict that visual processes can selectively up-weight certain visual stimuli at the level of pre-attentive processing (e.g. Guided Search; Wolfe, 2007); these results suggest that visual processes may also act to *down-weight* certain visual features pre-attentively, also. Additional research will be required to test this idea.

In sum, there appears to be a fixed, minimum length of time required for a given object to emerge from pre-attentive processes and to become available for attentional enhancement. Saliency does not appear to solely account for differences in this timing, nor the number of items that are selected for enhancement or the order in which they are selected. Although visual selective processes are probably capable of enhancing multiple items in certain search conditions, purely parallel object selection—meaning the selection of two or more items at the same time—may not be possible unless all items are equated for saliency and thus complete pre-attentive processing at the same time.

5.2. Object Identification Within a Reentrant Processing Network

Having considered how exogenous and endogenous factors influence attentional object selection, it is worth concluding this thesis by integrating these results within a biological model of visual information processing and enhancement. There are two critical elements to

address with such a model: how object perception arises, and how this perception is enhanced for certain objects over others.

Object perception is accomplished via the ventral visual pathway, comprising areas V1 through V4 and the inferotemporal lobe (IT). As information is exchanged and transformed along this pathway there are three important changes in neuronal properties. First, receptive fields grow larger in size: Whereas neurons in area V1 receive inputs from a region spanning approximately 0.5° of the field of view (Gattass, Gross, & Sandell, 1981), neurons in IT receive inputs from a region spanning 20° or more (Gross, Rocha-Miranda, & Bender, 1972). As a consequence, neurons integrate progressively more information at higher levels of processing. Second, individual neurons code for increasingly complex stimulus parameters at higher levels. Whereas a neuron in V1 might respond to a line of a particular orientation, a neuron in the inferior temporal lobe would respond to complex forms, such as an object (Desimone, Albright, Gross, & Bruce, 1984; Tanaka, Saito, Fukada, & Moriya, 1991). Third, there are extensive reciprocal neural pathways throughout the visual system, which permits higher areas to influence stimulus processing in lower areas (Felleman & Essen, 1991).

This hierarchical organization in turn accomplishes three important functions for visual processing. First, it solves the anatomical impossibility of having “grandmother” cells that uniquely code for all possible stimulus properties. Instead, complex stimuli are represented in a combinatorial manner based on specific patterns of activation from simple feature detectors (Tsotsos, 1990). By way of analogy, this is somewhat akin to the infinite level of abstraction that can be attained by combining the 26 letters of the English alphabet in a particular sequence.

Second, it solves an inherent biological limitation of information exchange within low-level processing areas. Although neurons within V1 and V2 can share information amongst themselves via lateral synapses, the axons that form these connections are unmyelinated and conduction velocity is therefore slow (approximately 0.1—0.3 m/s; Grinvald, Lieke, Frostig, & Hildesheim, 1994). This means that, in the span of approximately 100 ms, a given neuron at this level cannot integrate information beyond 1° of visual angle (Bullier, 2001). This is insufficient to generate a unified perception of the visual field. By contrast, afferent and efferent axons

between hierarchical levels are both myelinated and larger in diameter, and can transmit information at roughly ten times the rate of speed (>1 m/s; Girard, Hupé, & Bullier, 2001).

Third, this hierarchical structure emancipates high-level object representations from low-level stimulus properties. This is important for solving the dilemma of object constancy, which requires that the visual system be able to recognize an object despite differences in retinal image, viewpoint, illumination, and partial occlusion. At the highest level, a neuronal response can be triggered by a vast configuration of incoming information. As information is passed from V1 up to IT, neuronal processing transforms this representation from a retinal image to a series of conceptual object identities. In processing this information, the basic sensory information encoded in lower-level areas, such as V1 and V2, is generally inaccessible to higher cortical areas in the completion of most visual tasks (Crick & Koch, 1995).

Object perception emerges from the iterative exchange of information between low- and high-level cortical areas, which are connected by extensive reentrant pathways. Following stimulus presentation, the initial information provided to the visual system is supplied by the faster magnocellular pathway, which features very good contrast sensitivity but poor chromatic sensitivity and very poor spatial resolution (Maunsell, Nealey, & DePriest, 1990). This information is transmitted rapidly to higher cortical areas and activates a series of low-resolution perceptual templates, which are returned to lower level areas. This process is very fast, with reentrant signals arriving at V1 within approximately 125 ms (Heinen, Jolij, & Lamme, 2005). The timing of this initial reentrant signal is crucial, as the vast majority of information transmitted by a neuron occurs within about 125 ms of stimulus presentation (Heller, Hertz, Kjær, & Richmond, 1995). From here, the object representations activated in high-level areas are compared against the pattern of ongoing activities in low-level areas. Representations with low correspondence against these low-level activities are rejected, and the representation with the highest correspondence eventually leads to conscious awareness (Di Lollo, 2012).

5.2.1. Attentional Object Enhancement

A consequence of distributed object representations is that it can—and often does—result in conditions in which neurons encode features belonging to multiple objects. This is well

illustrated by visual search targets defined by a conjunction of features, such as a green circle among red circles and green diamonds. Here, a given IT neuron is supplied with information from low-level neurons for green, red, circle and diamond, but because the receptive fields of the low-levels neurons overlap, their outputs do not code uniquely for each object. This problem is made worse as additional nontargets are added, as this increases the amount of ambiguous, overlapping information encoded by neurons (Luck, Girelli, et al., 1997).

To resolve these ambiguous situations, the visual system can selectively bias the processing of visual stimuli by enhancing certain features and suppressing others. This was initially demonstrated by recording from monkeys as they performed a simple attention task (Moran & Desimone, 1985). When a relevant and an irrelevant item were presented within the same receptive field of a V4 neuron, the response to the irrelevant item was reduced. No such reduction in activity was observed when one item was presented within the neuron's receptive field and the other beyond it (see also Luck, Chelazzi, Hillyard, & Desimone, 1997). A similar study by Chelazzi and colleagues (Chelazzi, Miller, Duncan, & Desimone, 1993) reported large attention effects in a simplified visual search task when a target and distractor were presented within the same receptive field, this time defined by complex stimuli that could not be discriminated on the basis of simple object features.

On the basis of these animal studies, Luck, Girelli et al. (1997) provided converging evidence that the scalp-recorded N2pc is functionally related to this process of neural ambiguity resolution. Evidence in support of this proposition comes from the following. First, the N2pc was observed to be larger in amplitude when participants evaluated the target than when they simply reported the presence of the target, consistent with the idea that such evaluative tasks require the comparison of a higher-resolution template (Luck, Girelli, et al., 1997). Second, the onset of the N2pc (~175 ms) corresponded with the onset of attentional modulation from primate studies (Chelazzi et al., 1993). Third, the N2pc is highly contralateral, and neurons in V4 and IT are known to respond almost exclusively to stimuli in the contralateral hemifield.

Neural ambiguity resolution is closely linked with processes involved in computing object salience. These salience calculations are essential for determining what stimuli need to be resolved ahead of others (Itti, Koch, & Niebur, 1998; Laurent Itti & Koch, 2001). On a biological

level, neural responses to a given stimulus can be substantially modulated by the presence of other stimuli close to—but outside—the receptive field of a given neuron. When the surrounding stimuli are similar to the central stimulus, they suppress neural activity in the central neuron. Conversely, when the surrounding stimuli are markedly different to the central stimulus, no such inhibition occurs (Allman et al., 1985; Sillito, Grieve, Jones, Cudeiro, & Davls, 1995). Of course, these computations can also be influenced by top-down factors under the control of the observer. In fact, as demonstrated in Chapter 2, top-down factors can be sufficiently powerful to create salience even when none exists on the basis of local contrasts.

One final idea relates to the capacity of the visual system to selectively enhance more than one item. This has been a very long-standing debate among vision researchers. A key idea from this thesis is that attentional object enhancement is not restricted to a single item, which is strongly supported by N2pc data reported in this thesis in Chapter 4 and from several other recent N2pc studies on the subject (Eimer & Grubert, 2014; Grubert & Eimer, 2015, 2016; Jenkins et al., 2016; see also Mazza, Pagano, & Caramazza, 2012). This ability to operate on multiple conspicuous objects also extends to cases when a task-relevant singleton is presented in tandem with a task-irrelevant singleton. Here, distinct and concurrent processes can be elicited for the enhanced representation of the relevant item and the suppression of the irrelevant one (Gaspar & McDonald, 2014).

One intriguing possibility is that the number of items that can be operated upon—either via enhancement or suppression—is linked to the number of objects that can be retained in visual short-term memory (VSTM). Typically, humans can retain information about the properties of three or four visual items, but substantial and robust differences exist between individuals in the number of items that can be remembered. The ability to operate on two singletons may be restricted in those individuals that struggle to accurately retain even two items in VSTM. Preliminary evidence in support of this comes from a study conducted by Gaspar and colleagues (Gaspar et al., 2016), which tracked the N2pc and P_D components, thought to reflect the enhancement and suppression of singleton items, respectively. In that study, participants varied in their suppression of a salient distractor depending on their VSTM capacity. In the lowest-capacity participants, who scored an average VSTM capacity of just under two items, there was evidence not for suppression but for enhancement of the distractor. This may

correspond to a computationally simpler approach by the visual system—rather than “enhance one object and suppress the other”, the computational architecture may have engaged in the comparatively simpler process of “enhance both objects”. There are likely substantial, important discoveries to be made with respect to these individual differences in how the visual system selectively up- and down-weighs certain information.

As a final takeaway point, this thesis highlights the importance of combining indirect measures of attentional selection (such as RT) with direct measures of underlying biological processes (such as ERPs). By themselves, behavioral measures are often insufficient to unambiguously resolve many of the long-standing debates within modern cognitive psychology. For example, they are unable to unambiguously differentiate serial selection from parallel selection, cannot definitively isolate hybrid selection, and cannot conclusively identify salience-driven and goal-driven selection processes. Although not a focus of this thesis, they are also of limited value in understanding suppressive mechanisms that can be employed to prevent salience-driven capture. Other methods, and the ERP method in particular, will continue to offer compelling, additional information that can help to resolve many of these outstanding debates in cognitive psychology.

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