THE ROLE OF PRIMATE SUPERIOR COLLICULUS IN NATURALISTIC VISUAL SEARCH BEHAVIOR

by

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Abstract

Primates, including humans, explore their visual environment with sequences of gaze fixations interrupted by saccadic eye movements that re-orient the fovea to objects of interest. This visual behavior is thought to involve two separate processes. First, the current foveal image is analyzed and the next object of interest is selected as a saccade target. Second, previously examined objects are retained to prevent their re-examination. Visual behavior has been studied successfully using the visual search paradigm, in which subjects locate a unique target stimulus from amongst multiple distracting stimuli. Models of visual search posit that the process of saccade target selection is guided by a visual salience map. This map receives both stimulus-driven and goal-directed inputs to form representations of visual objects, and a competition between those representations is played out to determine the next saccade target. Neurophysiological studies using nonhuman primates have suggested that the salience map is distributed across a network of brain areas that includes the midbrain superior colliculus (SC). These studies, however, have not ruled out the possibility that selective activity for a saccade target may instead be related to the preparation of the saccade. Moreover, not much is known about the selection of a saccade target beyond the first in a sequence of gaze fixations. Finally, the mechanisms underlying the process of saccade target retention are not well understood. In this thesis, I will investigate the role of the primate SC in visual behavior by recording the activity of single neurons while monkeys perform visual search tasks. The major findings will describe 1) how SC sensory-motor neurons instantiate the visual salience map; 2) how this salience map is dynamically updated so that saccade targets are retained; and 3) how multiple representations on this salience map are processed in parallel for saccade target selection. Given SC’s role in the control of visual behavior and its position within the network involved in cognitive processes, these findings have important implications for our understanding of the neural basis of human cognition and of its dysfunctions in disease states.
Co-Authorship

Dr. Martin Paré was the principal investigator and supervisor for the studies described in this thesis. Dr. Paré conceived and designed research protocols for Chapter 2. I assisted Dr. Paré in conceiving and designing research protocols for Chapters 3 and 4. I was responsible for all of the data collection and analysis. I produced the first draft of this thesis and subsequent drafts included editorial submissions from Dr. Paré.
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Chapter 1

General Introduction
Visual exploratory behavior involves sequences of gaze fixations interrupted by saccadic eye movements that re-direct the fovea to areas of interest. On each fixation, the process of analyzing the foveal image occurs concurrently with the selection of the next peripheral saccade goal. In addition, there exists a parallel process by which previously examined visual objects or locations are retained. The visual search paradigm has been extensively used to study the allocation of covert visual attention in human subjects. In visual search tasks, subjects are asked to determine the presence or location of a uniquely defined target from amongst multiple distracter stimuli. Previous studies have described how covert attentional shifts during visual search allow for the preferential processing of visual details based on either their spatial location or their features (e.g., Treisman and Gelade, 1980; Wolfe et al., 1989). Saccadic eye movements can be considered as overt shifts of spatial attention. Moreover, there exists a vast body of literature that describes a functional – and practically obligatory – link between covert and overt shifts of attention (for review, see Findlay and Gilchrist, 2003). Consequently, the use of visual search tasks in which the eyes are free to move has been of great value for studying visual behavior (also see Findlay, 2009). Recording neuronal activity in monkeys trained to perform overt visual search tasks therefore provides an effective approach with which to investigate the neural mechanisms underlying the processes of saccade target selection and retention (for review, see Paré et al., 2009).

The study of saccade target selection and retention has been informed by current theories of visual search and attention. These models propose that the process of selecting a saccade target is guided by a visual salience map (Olshausen et al., 1993; Wolfe, 1994; Itti and Koch, 2000; Hamker, 2006). Representations of visual objects on this two-dimensional topographic map are the result of both stimulus-driven (bottom-up) inputs as well as goal-directed (top-down) signals (Fig. 1.1). Bottom-up inputs are derived from feature maps that simultaneously represent different properties of visual objects such as color, orientation, or shape. These feature maps might be
**Figure 1.1 The visual salience map**

Illustration of the theoretical visual salience map based on most models of visual attention and visual search. Its inputs include both stimulus-driven (bottom-up) signals from feature maps and goal-directed (top-down) signals. A retention process prevents a previously examined representation from being selected again. The competition between representations on the salience map is commonly resolved via winner-take-all mechanisms, and the salience map provides a single output to a separate motor map. Illustration is adapted from Hamker (2006).
instantiated by neurons in extrastriate (e.g., V4: Bichot et al., 2005) and inferotemporal (e.g., Chelazzi et al., 1998) cortex that have selective responses for different features and combinations of features. Top-down influences on the theoretical salience map include knowledge of target identity as well as prior history. Neurons in the prefrontal cortex are believed to provide such signals, as they have been shown to represent task goals and possibly modulate ongoing behavior (e.g., Rossi et al., 2007; for review, see Miller and Cohen, 2001). The salience map is considered to be ‘featureless’, having no selectivity for specific features. The magnitude of each representation dictates the probability of selecting that item for further processing, and in the case of overt visual search, the probability of selecting that item as the next saccade target. The resolution of the competition between the multiple visual representations is usually modeled as a winner-take-all mechanism, which then provides a single output signal specifying the next target of interest and a single motor representation to a downstream motor map (e.g., Glimcher et al., 2005). In these models, once an item has been selected its representation is removed from the salience map so that it will not be selected again. Neurophysiological studies of visual search have suggested that neurons within the frontal eye fields (FEF), lateral intraparietal area (LIP) and superior colliculus (SC) form a distributed salience map. These neurons initially have indiscriminate visually evoked responses to stimuli in their receptive fields (RF) and are therefore not considered to be feature selective. Their activity, however, evolves to select the saccade target before saccades: The target-related activity increases while the distracter-related activity does not (Thompson et al., 1996; Bichot and Schall, 1999; McPeek and Keller, 2002b; Ipata et al., 2006; Thomas and Paré, 2007). The activity associated with each stimulus predicts the probability of selecting that stimulus (Thompson et al., 2005a; Shen and Paré, 2006b; see also Bichot and Schall, 1999). A winner-take-all resolution of the competition is also evident in these neurons, as the stimulus associated with the greatest activity before saccades is the one that is selected, and this also holds for error trials when a distracter is incorrectly foveated (Thompson et al., 2005a;
Shen and Paré, 2007). Cortical involvement in this visuo-motor network has recently been reviewed (Thompson and Bichot, 2005; Bichot and Desimone, 2006; Goldberg et al., 2006; see also Fecteau and Munoz, 2006; Johnston and Everling, 2008). Here, I focus on the role of the superior colliculus within the network.

The SC is a laminar structure located on the dorsal surface of the midbrain. Its anatomical and physiological connections have been thoroughly reviewed (Sparks, 1986; May, 2006; also see Isa and Hall, 2009). Briefly, the intermediate layers receive a variety of inputs from both cortical and subcortical structures including substantia nigra pars reticulata, the extrastriate cortex and higher visual cortical areas, such as the FEF and area LIP (Fig. 1.2). Neurons in the SC superficial layers receive inputs from both the retina and visual cortex. The outputs from SC intermediate and deep layers include the pontine and midbrain circuits for horizontal and vertical saccade generation, respectively (for review, see Sparks, 2002).

Owing to its position in the saccade generating system, the SC is crucial to the initiation and control of saccades (for review, see Sparks, 1986). Microstimulation of the intermediate and deep layers of SC elicits saccades of predictable amplitudes and directions 20-30 ms following stimulation, revealing its organization as a retinotopic map of saccade vectors (Robinson, 1972; Schiller and Stryker, 1972). While the complete removal of both SC and FEF results in the inability to produce visually guided saccades (Schiller et al., 1980), there seems to be an obligatory role for SC as evidenced by long-term deficits that are not observed when FEF is lesioned (Schiller et al., 1987). Earlier proposals that there might exist two parallel pathways from each of FEF and SC to control saccades are not supported by evidence that FEF microstimulation following the reversible inactivation of SC does not elicit saccades (Hanes and Wurtz, 2001). Indeed, neurons in the SC intermediate layers directly output to the saccade generator circuit in the brainstem (Rodgers et al., 2006; see also Gandhi and Keller, 1997).
Figure 1.2 Neural circuitry of visual behavior
Schematic of brain regions involved in generating saccadic eye movements. Visual information from multiple extratriate cortical areas converges onto areas in the prefrontal and posterior parietal cortex, as well as superior colliculus. The central anatomical location of the superior colliculus, with its direct and indirect inputs from cortical visual processing centers along with its direct outputs to the brainstem saccade generating circuit, highlights the role this structure plays in cognitive processes and the control of saccades.
Neurons in these layers show a high-frequency burst of activity 18-20 ms prior to saccades (Sparks, 1978). Moreover, in a stop-signal task, these neurons have activity patterns necessary to control the production of saccades: Neurons discharge differently before countermanded saccades as compared to executed ones (Paré and Hanes, 2003). This activity change occurred with enough time to influence behavior, on average 10 ms before cancellation – the majority of neurons changed their activity before the estimated minimal efferent delay of 8 ms (Miyashita and Hikosaka, 1996). That these neurons discharged less on cancelled trials suggests that the activity must reach a critical threshold before a saccade is triggered.

The SC is conserved across all vertebrates, its homologue being the optic tectum in non-mammals. In primates, it receives functional projections from LIP, FEF and PFC (Fig. 1.2) (see Wurtz et al., 2001). These frontal and parietal areas in turn receive projections from striate and extrastriate areas (e.g., Baizer et al., 1991; Schall et al., 1995). The SC also has functional projections back to FEF (Sommer and Wurtz, 2004a, b; Berman et al., 2009) and extrastriate areas (Berman and Wurtz, 2010; also see Lyon et al., 2010) via subcortical areas to impact behavior. Neurons throughout this network have been shown to be involved in cognitive processes such as visual working memory (Chafee and Goldman-Rakic, 1998; see also Awh and Jonides, 2001; Curtis and D'Esposito, 2003) and visual attention (Shipp, 2004; Moore, 2006). The SC, then, is well positioned to study such cognitive processes as it integrates all of these cortical inputs and is able to more closely impact behavior. Due to this visuo-motor network’s involvement in cognitive processes, I will hereafter refer to it as the neuro-cognitive network.

The role of the neuro-cognitive network in the allocation of both overt (i.e., saccadic eye movements) and covert shifts of spatial attention has been of particular interest to neurophysiologists. Visual spatial attention is most commonly associated with an increase in the activity of neurons whose visual receptive fields are at those locations. Such modulation has been well documented not only in visual cortical areas (Treue and Maunsell, 1996; Reynolds et al.,
1999; McAdams and Maunsell, 2000) but also in area LIP (Goldberg et al., 2006), FEF (Thompson et al., 2005b) as well as in SC (Goldberg and Wurtz, 1972; Kojima et al., 1996; Kustov and Robinson, 1996; Ignashchenkova et al., 2004). These changes in activity could, however, merely correspond to changes in motor preparatory activity, especially for those data from SC. More conclusive evidence that neuronal activity reflects visual attention is provided by examining the allocation of feature-based attention, which gives us the ability to preferentially process certain attributes of visual details irrespective of their locations. The best evidence for this is in visual cortex, where neurons selective for a given feature show enhanced responses when monkeys are instructed to allocate their attention to that feature (Motter, 1994; Treue and Martinez-Trujillo, 1999; McAdams and Maunsell, 2000; Chelazzi et al., 2001; Bichot et al., 2005). Similar modulation in cortical sensory-motor neurons has been reported, even though the activity of these neurons is normally not selective for visual features (Bichot et al., 1996; Bichot and Schall, 1999, 2002; Toth and Assad, 2002; Sereno and Amador, 2006; Freedman and Assad, 2009). For example, FEF neurons recorded while monkeys search for a stimulus that has a unique conjunction of features show enhanced activity when the stimulus in their receptive fields is a distracter that shares a feature with the search target (Bichot and Schall, 1999). This feature-based modulation has been shown to be under the influence of goal-directed signals as the enhancement is maintained during the entire visual search session and its magnitude depends on the features of the target in the previous experimental session (Bichot and Schall, 1999).

1.1 Scope of study

Previous studies of the involvement of SC in saccade target selection using the visual search paradigm have demonstrated how neurons in the intermediate layers signal the location of the saccade target before single saccades (McPeek and Keller, 2002b) and they signal the saccade goal even on erroneous trials (Shen and Paré, 2007). Moreover, the focal inactivation of SC
during visual search results in the inability to select a search target that appears in the affected region of the visual field but search performance remains intact when the target appears in other locations (McPeek and Keller, 2004). These previous findings, however, cannot unequivocally rule out the possibility that the enhancement in neuronal activity is merely related to the programming of the saccade goal due to the confound that the attended stimulus and saccade goal are in the same spatial location. The SC may instead instantiate a motor map separate from the cortical visual salience map. Other findings allude to a greater role of SC in visual behavior as neurons in the intermediate layers carry signals of stimulus identity in addition to those associated with saccade programming, suggesting that there exists a selection threshold separate from the saccade trigger threshold (Shen and Paré, 2007). Moreover, I have previously reported how the activity of these sensory-motor neurons predicts the probability of selecting each stimulus in the search array (Shen and Paré, 2006b). Similar observations have been made in FEF whereby the preferential selection of a distracter stimulus that was the previous session’s target was accompanied by an enhancement in its neural representation (Bichot and Schall, 1999). These previous studies have used either feature search displays where the target is defined by a single feature or conjunction search displays where the target is defined by a unique combination of features and the distracters may or may not share a feature with the target. The distracter types appeared in balanced proportions in the conjunction search tasks, and in all cases, the search array was concentrically arranged around a central fixation stimulus. Manipulating the context within which the target appears, however, can provide additional insights. For example, varying the ratio of same-color:same-shape distracters on every presentation has shown how both humans (Kaptein et al., 1995; Bacon and Egeth, 1997; Shen et al., 2000; Sobel and Cave, 2002; Shen et al., 2003) and monkeys (Shen and Paré, 2006a) guide their behavior flexibly from trial to trial depending on the featural context of the search display. The neural instantiation of the visual salience map must be similarly adaptive to different featural contexts independent of saccade programming. I
adopted the variable distracter-ratio paradigm to definitively test whether SC is part of the distributed salience map. In Chapter 2 of this thesis, I will test the hypothesis that feature-related SC neuronal activity predicts the flexible behavior observed in different visual contexts. As both stimulus-driven and goal-directed signals must be present at the level of the salience map, I also determine whether there is a top-down feature-related enhancement for distracters that were the target of the previous session in addition to the bottom-up signals provided by the search array.

Current theories of visual attention and visual search suggest that in addition to the process of selecting the next saccade goal, there is a process by which objects that have already been examined are retained to prevent re-fixations (Cave and Wolfe, 1990; Itti and Koch, 2000; Hamker, 2006). In these models, the retention process is perfect whereby items are sampled without replacement. Visual search studies, however, have reported how this retention process is limited only to a few items as determined by the frequency at which subjects re-fixated previously examined items (Horowitz and Wolfe, 1998; Gilchrist and Harvey, 2000; McCarley et al., 2003). The existence of a limited retention capacity suggests that representations of previously examined items within the visual salience map are made temporarily irrelevant in order to guide behavior towards items that have not yet been examined. In order to study the mechanisms underlying this retention process, I adopt a conjunction search task that has large displays to encourage the occurrence of sequences of multiple fixations. The displays are also arranged in a grid based on the vector of the neuron’s visual receptive field such that the stimulus- and saccade-related activity can be examined in a tractable way from fixation to fixation. In Chapter 3, I test the hypothesis that monkeys, like humans, have a limited capacity for the retention of previously examined items by determining the rate at which they re-fixate those items. I also test the hypothesis that the process of saccade target retention is accomplished by the temporary suppression of SC neuronal activity associated with a previously examined distracter.
Most neurophysiological studies of visual search have focused on the neural mechanisms underlying the selection of the first saccade target following the presentation of the search display (e.g., Thompson et al., 1996; McPeek and Keller, 2002b; Thomas and Paré, 2007). Visual behavior, however, naturally involves sequences of fixations in a stable visual environment. In Chapter 4, I examine how the visual salience map guides behavior beyond the first saccade using the aforementioned grid array search task. It is consistently reported in visual search tasks how in a sequence of two saccades, the second is produced more quickly than the first (Viviani and Swensson, 1982; Hooge and Erkelens, 1996; Theeuwes et al., 1998; McPeek et al., 2000; McPeek and Keller, 2001; see also Sommer, 1997; Findlay et al., 2001; Godijn and Theeuwes, 2002). The target representation in SC has been shown to be enhanced despite an initial incorrect selection of a distracter stimulus, suggesting that it remains competitive on the visual salience map past the first saccade (McPeek and Keller, 2002a; Shen and Paré, 2007). Similarly, Murthy and colleagues (2007) reported how movement-related activity of FEF neurons arose early for the second saccade when monkeys had to correct their gaze fixation following a change in target position. These studies suggest that the selection of a saccade goal after the first fixation can occur before the fixation preceding target acquisition. The conclusions reached by these previous studies are limited, however, as the analysis was limited only to the time before the first saccade (McPeek and Keller, 2002a; Shen and Paré, 2007) or the second saccade target was not positioned ideally in a concentric array (Murthy et al., 2007). The neural mechanisms underlying the selection of a subsequent saccade target in active vision remain unclear. In this third study, I test the hypothesis that a subsequent saccade target is selected concurrently with the preceding one by comparing the activity of SC neurons between multi- and single-fixation trials.

Altogether, these studies will show how the superior colliculus is a part of the visual salience map within the neurocognitive network and is uniquely positioned to influence behavior. I will also describe the role of the superior colliculus in active vision, specifically its involvement
in both the process of saccade target selection and retention. Finally, I will discuss the implications of these findings on our understanding of the neural mechanisms underlying visual behavior in naturalistic environments.
1.2 References


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Chapter 2

Neural basis of feature-based contextual effects on visual search behavior
2.1 Abstract

Searching for a visual object is known to be adaptable to context, and it is thought to result from the selection of neural representations distributed on a visual salience map, wherein stimulus-driven and goal-directed signals are combined. Here we investigated the neural basis of this adaptability by recording superior colliculus (SC) neurons while three female rhesus monkeys (Macaca mulatta) searched with saccadic eye movements for a target presented in an array of visual stimuli whose feature composition varied from trial to trial. We found that sensory-motor activity associated with distracters was enhanced or suppressed depending on the search array composition and that it corresponded to the monkey's search strategy, as assessed by the distribution of the occasional errant saccades. This feature-related modulation occurred independently from the saccade goal and facilitated the process of saccade target selection. We also observed feature-related enhancement in the activity associated with distracters that had been the search target during the previous session. Consistent with recurrent processing, both feature-related neuronal modulations occurred more than 60 ms after the onset of the visually evoked responses, and their near coincidence with the time of saccade target selection suggests that they are integral to this process. These results indicate that SC neuronal activity is shaped by the visual context as dictated by both stimulus-driven and goal-directed signals. Given the close proximity of the SC to the motor circuit, our findings suggest a direct link between perception and action and no need for distinct salience and motor maps.
2.2 Introduction

Our ability to select a visual object from amongst numerous alternatives is thought to be guided by a visual salience map (Cave and Wolfe, 1990; Findlay and Walker, 1999; Itti and Koch, 2000). Visual representations on the salience map are the result of both stimulus-driven (bottom-up) inputs as well as goal-directed (top-down) signals. The magnitude of each representation is related to the probability of selecting that object for further processing and, in the case of overt visual search, as a target for the next saccadic eye movement. Stimulus discriminability is crucial to determining visual behavior when searching for a target stimulus amongst distracter stimuli (Treisman, 1988; Duncan and Humphreys, 1989; Wolfe et al., 1989): If discriminability is high, the representation of the search target on the visual salience map is significantly greater than those of distracter stimuli, resulting in a target that seems to ‘pop-out’. If target discriminability is low, as when the target is defined by a conjunction of features, the representations are more similar and subjects are less likely to select the search target. Visual behavior is also influenced by prior information such as knowledge of target features and recent past experience. Visual search studies have shown that both humans and monkeys are more likely to make saccades to stimuli that share features with the target of the current search session (Findlay, 1997; Motter and Belky, 1998) or of the previous one (Bichot and Schall, 1999a).

Neurophysiological studies of visual search in monkeys have demonstrated how the visual salience map is distributed across a network of sensory-motor structures that include the lateral intraparietal (LIP) area (Ipata et al., 2006; Thomas and Paré, 2007), the frontal eye field (FEF; Thompson et al., 1996; Thompson and Bichot, 2005), as well as the superior colliculus (SC; McPeek and Keller, 2002; Shen and Paré, 2007). These neurons give visually evoked responses to stimuli falling in their receptive fields and subsequently signal the location of the saccade target before saccades are made. Neurons in area LIP and FEF are also influenced by prior information, showing feature-based modulations that are task-relevant as well as memory-
related (Bichot and Schall, 1999b; Toth and Assad, 2002), i.e., priming of distracter stimuli whose features were those of the target in the previous search session (Bichot and Schall, 1999b).

Stimulus discriminability is not only determined by individual stimulus features but also by the spatial organization of the search display. Perceptual grouping of objects, for instance, can facilitate visual search (Verghese and Nakayama, 1994; see also Duncan, 1995; Hegde and Felleman, 1999) as can the global composition of the search display as shown in studies using the variable distracter-ratio search task. In this task, the ratio of distracters sharing a feature with the search target is manipulated (Shen et al., 2000; Shen and Paré, 2006). Responses are fastest when there are few of one distracter type, with incorrect saccades being biased towards those distracters. Humans and monkeys naturally adapt their visual search strategies to visual context on a trial-by-trial basis (see also Egeth et al., 1984; Zohary and Hochstein, 1989; Poisson and Wilkinson, 1992; Kaptein et al., 1995; Bacon and Egeth, 1997; Sobel and Cave, 2002). This flexible allocation of resources can facilitate visual search by limiting the selection process to stimuli that are most relevant.

How saccade target selection is influenced by visual context is not known. Studies of contextual influences on visual processing using figure-ground segregation (Zipser et al., 1996; Lamme et al., 1999; Supèr et al., 2001) and curve tracing tasks (Khayat et al., 2006; 2009) have indicated that contextual modulation in visual cortex is most likely mediated by (top-down) cortico-cortical recurrent processing. This interpretation is supported by the late onset of the neuronal modulation (~100 ms following the visually evoked responses), which is in stark contrast with the early modulation (~20 ms) consistent with (bottom-up) feed-forward processing that have been observed in studies using pop-out stimuli (Knierim and van Essen, 1992; Nothdurft et al., 1999, 2000; Burrows and Moore, 2009). In this study, we investigated how the influence of visual context is exerted on the visual salience map by recording the activity of SC sensory-motor neurons while monkeys performed a variable distracter-ratio search task. We
tested the hypothesis that this influence has a goal-directed component by measuring the timing of the corresponding neuronal modulation and comparing it to those associated with saccade target selection as well as with the priming of stimulus features that occur between experimental sessions.

2.3 Materials and Methods

Data were collected from three female rhesus monkeys (*Macaca mulatta*, 4.5-6.0 kg, 8-10 years) cared for under experimental protocols approved by the Queen’s University Animal Care Committee and in accordance with the Canadian Council on Animal Care guidelines. The surgical procedure, stimulus presentation and data acquisition have been described previously (Shen and Paré, 2006, 2007). Monkeys were housed in large enclosures (Clarence et al., 2006) and received both antibiotics and analgesic medications during the post-surgery recovery period, after which they were trained with operant conditioning and positive reinforcement to perform fixation and saccade tasks for a liquid reward until satiation. The extra-cellular activity of single SC neurons was recorded using previously described methods (Paré and Wurtz, 2001), and spike occurrences were sampled at 1 kHz.

2.3.1 Behavioral paradigm

Monkeys first performed a visual delayed saccade task to characterize the discharge properties of the neurons and determine their receptive fields (Paré and Wurtz, 2001). This task temporally dissociated visual stimulation from saccade execution by introducing a delay of 500-1000 ms between the presentation of a stimulus in a neuron’s receptive field and the disappearance of the fixation stimulus, which acted as the signal for the monkeys to make a saccade to that stimulus. Neurons were included in our sample if they exhibited both visually evoked responses (≥ 10 sp/s) and saccade-related activity (≥ 100 sp/s) in this task.
The main data of this report were collected while monkeys performed a visual conjunction search task in which the stimuli were conjunctions of a color (red or green) and a shape (circle or square). On each trial, monkeys initially fixated a central stimulus that acted as a cue for the target. This stimulus disappeared with the simultaneous appearance of a concentric array of one target and 11 distracter stimuli. On each trial, either the target or a distracter stimulus appeared randomly in the center of the neuron’s receptive field, and all other stimuli were randomly positioned equidistant from the central stimulus position and from each neighboring stimulus. The ratio of same-color/same-shape distracters on each trial was varied randomly between 2/9, 6/5 and 9/2 (Fig. 2.1A). Monkeys were rewarded maximally for fixating the location of the pseudo-randomly positioned target stimulus within 500 ms of the display presentation, and were partially rewarded (<0.33 of the maximum amount along with the reinforcement tone) for locating it with multiple saccades within 2,000 ms of the initial eye movement. Trials were deemed correct if the monkey successfully foveated the target after a single saccade.

To familiarize monkeys with the target in the main task and quantitatively delimit each neuron’s receptive field, each block of search trials was preceded by 120 trials of a simple detection task. The search target first appeared as the fixation stimulus and then stepped to one of the 12 positions used in the conjunction search task.

2.3.2 Data Analysis

Only trials with stimulus-directed saccades were included in the data analysis. Details of the neuronal data analyses have been described previously (Thompson et al., 1996; Shen and Paré, 2007; Thomas and Paré, 2007). Neuronal activity was quantified as continuously varying spike density functions aligned on the onset of either the visual stimulus presentation (stimulus aligned) or the first saccade (saccade aligned). Spike density functions were constructed by convolving spike trains with a combination of growth (1-ms time constant) and decay (20-ms time constant)
Figure 2.1 Variable distracter-ratio visual search task and behavior

A. Task displays consisted of three possible same-color/same-shape distracter ratios: few same-color (2/9, left), balanced same-color (6/5, middle) and many same-color (9/2, right). All example displays show a correct single saccade (arrow) made to the target. B. Average index of stimulus salience (observed errors to same-color distracters – expected by chance) for three monkeys performing the variable distracter-ratio task; chance is equal to 0.182, 0.545, and 0.818, respectively. The overall proportions of first saccades to each distracter type were similar and relatively small across displays (few same-color displays, same-color: 0.15 ± 0.01 vs. same-shape: 0.11 ± 0.01; balanced displays, same-color: 0.19 ± 0.02, same-shape: 0.12 ± 0.01; many same-color displays, same-color: 0.20 ± 0.02, same-shape: 0.16 ± 0.02). Red: few same-color; blue: balanced; green: many. All values are mean ± SE.
exponential functions that resembled a postsynaptic potential (Thompson et al., 1996).

We used the data collected in the delayed saccade task to calculate a visuo-movement index (VMI; Shen and Paré, 2007; Thomas and Paré, 2007), which quantified the relative magnitude of visually evoked and saccade related activity of each neuron: 

\[ VMI = \frac{\text{vis} - \text{mov}}{\text{vis} + \text{mov}}, \]

where \( \text{vis} \) is the mean discharge rate over the first 100 ms following stimulus presentation (mean = 61 sp/s; range = 12-231 sp/s), and \( \text{mov} \) is the peak discharge rate within ± 40 ms of saccade onset (mean = 334 sp/s; range = 100-706 sp/s). The peak saccade related activity occurred on average 2.4 ± 0.7 ms before saccade onset. Neurons with stronger visually evoked activity have VMIs closer to 1.0 and those with stronger saccade related activity have VMIs closer to -1.0. The mean VMI value of the neuronal sample was -0.66 ± 0.03 (range = -0.97 – -0.19). Several neurons also exhibited sustained activity during the delay period of this task, and that activity was quantified as the mean discharge rate over the last 300-ms of the delay period (Paré and Wurtz, 2001).

We used the now common method (Thompson et al., 1996; Shen and Paré, 2007; Thomas and Paré, 2007) derived from Signal Detection Theory to quantify the separation between a neuron’s activity associated with the target and that associated with a distracter (trials in which the target was located in one of the seven opposing locations). Receiver operating characteristic (ROC) curves were built for successive 5-ms intervals by plotting the probability that the rate of target-related activity is greater than a criterion rate as a function of the probability that the rate of distracter-related activity is greater than that same criterion. The area under each of these curves (auROC) was plotted as a function of time, and the time course of neuronal discrimination captured by the Weibull function that fit best with the data (mean \( R^2 = 0.96 \), range: 0.82 – 1).

More than 15 target and 75 distracter trials were used to construct the ROC curves for each neuron. Best-fit functions were calculated only with activity occurring before the initiation of
saccades landing correctly on target, and they were terminated when there were fewer than five target or distracter (correct) trials. The ranges of response latencies in target and distracter trials were matched across all conditions. The discrimination magnitude of each neuron was defined as the upper limit of the best-fit functions, and the point at which these functions reached a criterion value of 0.75 was taken as the neuron’s discrimination time. Discrimination time occurred at least 13 ms before saccade initiation, and it was used to center a 25-ms analysis epoch to contrast the distracter-related modulation in neuronal activity: Modulation Index (MI) = (color – shape) / (color + shape) (Motter, 1994a; Treue and Martinez-Trujillo, 1999). To be included in any analysis, neurons had to contribute a minimum of five trials in each of the conditions considered. To estimate the time at which distracter related activities became significantly different from each other we conducted successive rank-sum tests on the same 5-ms intervals used for the ROC analysis (Thomas and Paré, 2007).

To test the relationships between neuronal activity variables as well as between neuronal activity and behavior, we performed permutation tests (10,000 iterations) of the slopes of the linear regression.

2.4 Results

2.4.1 Visual search strategy and stimulus salience

We recorded the activity of 42 sensory-motor neurons within the intermediate layers of SC while three rhesus monkeys (monkey F: 19; G: 10; H: 13) reported with a saccadic eye movement which of the stimuli in a visual search display had a unique conjunction of features. The distracter stimuli in this task could share either the color or the shape of the search target, and the ratio of same-color/same-shape distracters was randomly varied between 2/9, 6/5 and 9/2 from trial to trial (Fig. 2.1A). Monkeys correctly foveated the target with a single saccade with a mean (± SE) probability of 0.71 ± 0.02 and the latencies of their correct saccades averaged 192 ± 5 ms. We
quantified the effects of display composition on the animals’ behavioral strategy (i.e., eye movement choices) with a relative index of *stimulus salience* by taking the difference between the observed proportion of errors made to same-color distracters and that expected by chance (Shen and Paré, 2006). A positive index indicates how same-color distracters were treated as the most salient in a display while a negative index indicates how same-color distracters were least salient (i.e., salient same-shape distracters). Monkeys biased their search to the color dimension when same-color distracters were few (on average, stimulus salience: $0.42 \pm 0.04$; Fig. 2.1B) and away from it when there were many ($-0.23 \pm 0.04$). These effects of stimulus salience were significantly different from chance ($p < 0.05$, t test); no preference for either feature dimension was observed when distracter types were balanced ($0.09 \pm 0.04$; $p = 0.08$). Note that these biases were determined only from the small proportion of errors that monkeys made ($< 30\%$). Those distracters that were most unique in the unbalanced displays therefore did not automatically capture attention because of their physical salience (Yantis and Jonides, 1984; Theeuwes, 1990; Yantis and Jonides, 1990; Folk et al., 1992).

These results demonstrated that our monkeys, like humans (e.g., Egeth et al., 1984; Shen et al., 2000), limited their search to the features most relevant to the task on a trial-by-trial basis, as dictated by the visual context.

**2.4.2 Stimulus salience and saccade target selection**

The activity of all SC neurons in the variable distracter-ratio task was first indiscriminant, but it evolved to signal the target location: the activity associated with the target became enhanced and that associated with a distracter became suppressed. Consistent with previous studies (McPeek and Keller, 2002; Shen and Paré, 2007), visually evoked responses were not selective for either the type or feature of the stimulus presented in their receptive field across search displays (see Table 2.1). This was also the case within the *few same-color* and the *many same-color* displays,
when one distracter type was estimated to be more behaviorally salient. When and how well sensory-motor neurons selected the saccade target in each of the distracter-ratio displays was quantified with a discriminant analysis based on Signal Detection Theory, which computed the probability that an ideal observer could discriminate neuronal activity associated with target and distracter stimuli (McPeek and Keller, 2002; Shen and Paré, 2007). On average, neurons discriminated the target from any distracter 125 ± 3 ms following the onset of the search display and 61 ± 4 ms before the onset of the initial saccade that correctly landed on the search target. At these times, all 42 neurons had statistically greater activity associated with the target than that associated with distracters (p < 0.01, rank sum test). The discrimination magnitude of these neurons averaged 0.94 ± 0.01. Because this analysis only considers correct trials, such a high discrimination is expected from neurons whose activity is thought to reflect the process of selecting the search target and play a critical role in guiding behavioral choice (Schall, 2003).

Consistent with our previous report (Shen and Paré, 2007) as well as with observations in FEF (Thompson et al., 2005b; Trageser et al., 2008), the discrimination of SC sensory-motor neurons generally exceeded the overall accuracy of the search computed from each corresponding session, which averaged only 0.71 across all sessions. As a consequence, discrimination magnitude was not correlated with the overall probability of correctly foveating the target with a single saccade in each corresponding session (p = 0.83, Spearman rank correlation). This lack of correlation rules out task difficulty as a factor influencing target discrimination by SC neurons in correct trials.

Crucially, the activity associated with the more salient same-color distracter in the few same-color trials evolved to be greater than that related to the less salient same-shape distracter.
Visually evoked responses (mean ± SE), taken as the first 25-ms of each neuron’s response to the search display, did not vary across stimulus type, feature, and salience. Comparison of the visually evoked responses associated with stimulus types was done across display compositions. Direct comparisons of the visually evoked responses associated with stimulus features (color or shape) included both target and distracters, and were limited to a subset of neurons because each recording session involved only three of the four types of stimuli. Salient distracters were both the same-color distracter in the few same-color display and the same-shape distracter in the many same-color display. Non-salient distracters were both the same-shape distracter in the few same-color display and the same-color distracter in the many same-color display.

Table 2.1 Visually evoked responses in the variable distracter-ratio search task.

<table>
<thead>
<tr>
<th>Stimulus Type</th>
<th>Target</th>
<th>Same-color distracter</th>
<th>Same-shape distracter</th>
<th>One-way ANOVA on ranks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40 ± 5 sp/s</td>
<td>37 ± 5 sp/s</td>
<td>39 ± 5 sp/s</td>
<td>p = 0.92 (n = 42)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stimulus Feature</th>
<th>Signed rank-sum test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red circle</td>
<td>Green circle</td>
</tr>
<tr>
<td>41 ± 6 sp/s</td>
<td>40 ± 6 sp/s</td>
</tr>
<tr>
<td>p = 0.50 (n = 25)</td>
<td></td>
</tr>
</tbody>
</table>

| Red square       | Green square         |
| 38 ± 8 sp/s      | 37 ± 9 sp/s          |
| p = 0.40 (n = 17) |

| Red circle       | Red square           |
| 45 ± 9 sp/s      | 44 ± 9 sp/s          |
| p = 0.06 (n = 19) |

| Green circle     | Green square         |
| 34 ± 4 sp/s      | 33 ± 4 sp/s          |
| p = 0.09 (n = 23) |

<table>
<thead>
<tr>
<th>Stimulus Salience</th>
<th>Two-way ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same-color distracter</td>
<td>Same-shape distracter</td>
</tr>
<tr>
<td>34 ± 4 sp/s</td>
<td>36 ± 5 sp/s</td>
</tr>
<tr>
<td>display type: p = 0.96</td>
<td></td>
</tr>
<tr>
<td>interaction: p = 0.91</td>
<td></td>
</tr>
<tr>
<td>(n = 39)</td>
<td></td>
</tr>
</tbody>
</table>

| Same-color distracter | Same-shape distracter | in many same-color displays |
| 34 ± 5 sp/s | 37 ± 5 sp/s | distracter type: p = 0.58 |
| display type: p = 0.96 |
| interaction: p = 0.91 |
| (n = 39) |
(Fig. 2.2A, top). While the initial discrimination probability was the same when comparing target activity to each distracter type (Fig. 2.2A, bottom), the discrimination process was faster and more efficient for the non-salient distracter. When the distracter types were more balanced, the activation associated with each distracter type and its discrimination from the target were nearly identical (Fig. 2.2B). Finally, when same-shape distracters were more salient, activity associated with these distracters was enhanced and the discrimination of the same-color distracter was faster and more efficient (Fig. 2.2C). This modulation was quantified by taking the difference between each neuron’s discrimination magnitude and discrimination time of the target from the same-color and same-shape distracter (i.e., target/same-color – target/same-shape) in each display type. On average, discrimination magnitude was significantly higher when discriminating the target from the less salient distracters (Fig. 2.2D; p < 0.001, ANOVA). In addition, discrimination time was significantly shorter when discriminating the target from the less salient distracters (Fig. 2.2E; p < 0.001). Similar results were obtained when data were aligned to saccade onset (Fig. 2.2F; p < 0.001). In other words, the more numerous a certain distracter is, the more it is filtered out.

For the experimental sessions included in the above analysis, the stimulus salience observed in the corresponding sessions did not differ from that reported in Figure 2.1B (p = 0.52, rank sum test). The changes in discrimination ability observed in the corresponding neurons were also not related to the overall accuracy of the search computed from each corresponding search display: few same-color (p = 0.77, Spearman rank correlation), balanced (p = 0.30), many same-color (p = 0.77).

In summary, the process of selecting the saccade target, as reflected in SC sensory-motor neurons, depended on the flexible enhancement of a stimulus feature predicated by visual context.
Figure 2.2 Effects of feature sensitivity on saccade target selection

A-C, For a sample neuron in A, few same-color, B, balanced and C, many same-color displays. D, Effects of feature sensitivity on discrimination magnitude for the neuronal sample. E-F, Effects of feature sensitivity on discrimination time, with data aligned on either E, stimulus onset or F, saccade onset. Only neurons with significant discrimination reaching the criterion of 0.75 in all conditions were included in E and F.
2.4.3 Stimulus feature sensitivity is independent of saccade goal

To quantify the stimulus feature sensitivity of SC neurons, we compared the activity associated with the two types of distracter stimuli. Because these stimuli were not the goal of an eye movement, this analysis eliminates the possibility that the modulation was related to saccade programming. We computed a modulation index (MI) that contrasts the activity associated with each distracter type across conditions around the time that individual neurons discriminated a target from any distracter (Fig. 2.3). Positive indices indicate greater activity for same-color distracters, and negative indices indicate greater activity for same-shape distracters. Neuronal activity associated with same-color distracters was significantly greater than that associated with same-shape distracters when the former were fewer and presumed to be more salient (Fig. 2.3A; MI: 0.10; p < 0.01, t test), whereas it was significantly lower when they were more numerous and presumed to be less salient (Fig. 2.3C; MI: -0.16; p < 0.001). The activity associated with these distracters was not different when their proportions were balanced (Fig. 2.3B; MI: 0; p = 0.43). Moreover, the activity associated with the same-color relative to the same-shape distracter was 24% greater when the distracter-ratio was low and 28% less when the ratio was high (Fig. 2.3; p < 0.001).

This effect was indeed both an enhancement of the salient and a suppression of the non-salient distracter representations: When the activity associated with each distracter type in the few and many displays were compared to their activity in the balanced displays, the representations of salient distracters were enhanced by 19.5% and those of non-salient distracters suppressed by 9.2% (Fig. 2.4); these changes in activity were significantly different from zero (p < 0.05), and they were not restricted to a subset of the neuronal sample. The majority of the neurons showed both enhancement and suppression modulation in their activity, but those showing the most
Figure 2.3 Feature-based contextual effects on SC neuronal activity
A, few same-color, B, balanced and C, many same-color displays. The modulation index (MI) was calculated for each neuron using distracter-related activity during a 25-ms epoch centered on the neuron’s discrimination time, where MI = (color-shape)/(color+shape).
Figure 2.4 Enhancement and suppression of neuronal activity associated with salient and non-salient distracters.

Percent changes (modulation) were calculated relative to the (baseline) activity in the balanced displays. Each neuron’s activity was computed during a 25-ms interval centered on the neuron’s discrimination time. Salient distracters were both the same-color distracter in the few same-color display and the same-shape distracter in the many same-color display. Non-salient distracters were both the same-shape distracter in the few same-color display and the same-color distracter in the many same-color display. Bold axis labels: mean enhancement and suppression. Solid symbols: individual neurons with both activity enhancement and suppression that were not statistically significant ($p > 0.05$, rank sum test).
activity enhancement were not necessarily those showing the most suppression (p = 0.57, permutation test).

To determine when this stimulus feature sensitivity arose, we calculated the time at which the salient distracter activity became significantly greater than the non-salient distracter activity (p < 0.05, successive rank sum tests) and compared these to each neuron’s discrimination time. We found that feature sensitivity occurred, on average, 103 and 121 ms after the onset of the many and few same-color displays, respectively. This event corresponded to 59 and 76 ms after the onset of the visually evoked responses in these trials, and it did not occur significantly earlier than when neurons discriminated the target from any distracter (Fig. 2.5; many same-color displays: 100 vs. 114 ms, p = 0.25, N = 15, paired t test; few same-color displays: 121 vs. 90 ms, p < 0.001, N = 22). Across display types, feature sensitivity arose 69 ± 5 ms after the onset of the visually evoked responses and not before the time that neurons discriminated the target from any distracter (113 vs. 99 ms; p < 0.05, N = 37).

We also examined whether the variability of the feature-based modulation of SC activity can be explained by an individual neuron’s pattern of activity. First, we tested whether the discrimination ability of a neuron predicted this modulation. Neither the enhancement of salient distracter representations nor the suppression of non-salient ones was related to a neuron’s discrimination magnitude (enhancement: p = 0.41; suppression: p = 0.29, permutation test). Next, we tested whether a neuron’s modulation was related to its basic discharge properties observed in the delayed saccade task: More ‘visual’ neurons might show greater modulation than more ‘saccade’ ones. A neuron’s position along the visuo-movement axis (determined by its VMI) did not predict its modulation abilities (p = 0.91 and p = 0.11 for enhancement and suppression, respectively), nor did the strength of its saccade-related activity (p = 0.37 and p = 0.58). In addition, the enhanced activity of a neuron observed in the variable distracter-ratio task was
Figure 2.5 Time course of feature-based effects.
Mean ± SE stimulus onset, visual response onset, and discrimination time with respect to time at which feature-based modulation was significant (p < 0.05, rank sum test). Feature sensitivity in many (top) and few (middle) same-color displays, as well as between-session feature priming (bottom).
related to neither the strength of its visually evoked response (p = 0.64) nor its sustained activity during the delay period (p = 0.86) of the delayed saccade task. The only significant correlation that we found was between the suppression of a neuron’s activity and its visually evoked response (p < 0.01), though this relationship was relatively weak (R² = 0.19) and caused by two outlier neurons with strong visually evoked responses: it was also not corroborated by the correlation with the neuron’s delay activity (p = 0.10). These results argue against a neuron-specific contribution to this process, as has been shown in studies of spatial attention in both SC (Ignashchenkova et al., 2004) and FEF (Thompson et al., 2005a). While we cannot rule out different contributions by extreme classes of neurons, it is more likely that SC neuronal ensembles cooperate to enhance and suppress salient and non-salient features, which together perform a more efficient selection process (Shen and Paré, 2007; see also Bichot et al., 2001). Consistent with this population coding is the lack of correlation at the neuronal level between the enhancement of the salient distracter representation and the suppression of the non-salient distracter representation.

2.4.4 Stimulus feature sensitivity predicts visual search strategy

To what extent can the feature sensitivity of sensory-motor neurons account for the effects of stimulus salience on behavior? To answer this question and to determine the time course of these contextual effects, we examined the relationship between the behavioral index of stimulus salience and the neuronal modulation index during three analysis epochs related to events within the discrimination process that were common across recording sessions despite the different response latencies: 1) when the neuron first responded to the visual stimulation, 2) when the neuron discriminated the target from any distracter, and 3) just prior to saccade initiation (Fig. 2.6). A value in the upper-right quadrant of this graph would indicate that a behavioral attraction
Figure 2.6 Time course of feature-based contextual effects across visual search displays.

Relationship between the neuronal modulation index and the corresponding behavioral index of stimulus salience during A, the visual response (25 ms from visual response latency), B, the discrimination (25 ms centred on the time neurons discriminated target from any distracter) and C, the pre-saccade (25 ms before saccades) epochs. Diamonds: few same-color displays; squares: balanced same-color; triangles: many same-color. Statistical values are from permutation tests (10,000 iterations) of the slopes of the linear regression.
towards the presumably salient same-color distracter is associated with an increased neuronal sensitivity for that same distracter type. A value in the lower-left quadrant refers to a behavioral aversion to the same-color distracter associated with a reversed neuronal sensitivity to that distracter. Early in the discrimination process, the visual responses to each distracter could not predict the effects of stimulus salience on behavior (Fig. 2.6A; p = 0.35, permutation test). This result was anticipated because the display composition changed randomly from trial to trial. By the time neurons discriminated the target from any distracter, neuronal activity was predictive of behavior (Fig. 2.6B; \( R^2 = 0.35, p < 0.0001 \)), and it further improved just before saccades (Fig 2.6C; \( R^2 = 0.48, p < 0.0001 \)).

The results of the above correlation analyses capture the match between the bias in modulation index and that in the stimulus salience expressed primarily in the two unbalanced search displays. A stronger link between neuronal activity and behavior could be made if the variability within these biases were also correlated within the balanced condition, i.e., when stimulus context was controlled. Although the distribution of modulation indices in the balanced displays was centered on zero, some neurons displayed activity modulation that was either significantly positive or negative (Fig. 2.3B). We therefore examined whether the variability between neurons in balanced displays could account for some of the variability in search strategy between sessions. We found that this was the case just before saccades were initiated away from the neurons’ receptive fields (\( R^2 = 0.15, p < 0.0001 \), permutation test) as well as when the neurons discriminated the target from any distracter (\( R^2 = 0.21, p < 0.01 \)), but not during their initial visually evoked responses (\( p = 0.69 \)). Even within a single trial condition, i.e., when both the task difficulty is unchanging and the distracter-ratio is balanced and constant, the variability in activity between neurons accounts for some of the variability in visual search behavior. The activity related to a distracter stimulus during correct trials – when a saccade is made away from that distracter – can therefore predict stimulus salience estimated from behavior in error trials. In
other words, a neuron’s activity associated with a type of distracter (not a particular spatial location) predicts the general probability of saccades made erroneously to that type of distracter (not a particular saccade goal).

2.4.5 Priming of stimulus feature sensitivity

One possible contribution to the feature-related signals observed in the balanced condition could be between-session priming of stimulus feature. Priming is known to affect FEF activity when the current session’s target shares a feature with the target of the previous day (Bichot and Schall, 1999b). Similar to previous behavioral reports of conjunction search, monkeys’ preferences for one target feature over the other was influenced by the previous session’s target identity: In balanced display trials, the behavioral index of stimulus salience was greater (i.e., monkeys were more biased for same-color distracters) when the previous session’s target had the same color than if it had the same shape (Fig. 2.7A; 0.15 ± 0.03 vs. -0.10 ± 0.08, p < 0.05, rank sum test). The stimulus salience index during color-primed sessions was also significantly greater than 0 (p < 0.01, t test). Figure 2.7B illustrates, using two sample neurons, how distracter-related activity was affected by feature priming: initial visual responses were the same, but the activity associated with the distracter having the primed feature was greater by the time the neurons discriminated the target from any distracter. The neuronal modulation index was quantified for the subset of neurons recorded during either color- or shape-primed sessions. Calculated around the time of discrimination, the modulation index during color-primed sessions was significantly greater than 0 (Fig. 2.7C; p < 0.05, t test) and was also significantly different from that during shape-primed sessions (p < 0.05, rank sum test).

We tested whether there was still a relationship between the observed neuronal modulation and behavior in the absence of feature-based priming by considering the balanced
Figure 2.7 Effects of between-session priming in balanced displays.

A, Average (± SE) index of stimulus salience for two monkeys (G and H) in either color- (N = 8) or shape-primed (N = 11) sessions. B, Two sample neurons’ activities in balanced display trials during sessions that were either color- (left) or shape-primed (right). Green: same-color distracter, pink: same-shape distracter, black: target. Black bars indicate the occurrence of saccades made to the target. C, MI at DT in balanced displays during sessions that were either color- (black) or shape-primed (gray).
display condition for only the sessions in which the previous session’s target did not share any features with the current target (i.e., no feature priming). Even in these sessions, the behavior varies from session-to-session and can be predicted by the activity variability between neurons at the time of discrimination (p < 0.05, N = 12, permutation test).

To determine when the effect of between-session feature priming arose on neuronal activity, we calculated the time at which the primed distracter activity became significantly greater than the non-primed distracter activity (p < 0.05, successive rank sum tests). We found that the onset of feature-based priming occurred, on average, 79 ± 8 ms after the onset of the visually evoked responses (Fig. 2.5, bottom) and around the time that neurons discriminated the target from any distracter (115 vs. 101 ms; p = 0.06, N = 13, paired t test). The timing of this between-session feature priming is comparable to that of the stimulus feature sensitivity.

2.5 Discussion

We observed modulation in the sensory-motor activity of SC neurons associated with distracter stimuli in a visual search display whose feature composition varied from trial-to-trial as well as when a feature was primed by a previous experimental session. This feature-based contextual modulation was associated with stimuli that were not the goal of an eye movement, thereby eliminating the spatial confound that it was related to saccade programming. Its magnitude did, however, correlate with the visual search strategy of the monkeys, as assessed by the distribution of their occasional errant saccades, and facilitated the process of saccade target selection. The late onset of this feature-based modulation with respect to visually evoked responses indicates that it was not purely stimulus-driven, but that it also had a goal-directed component. Its near coincidence with saccade target selection suggests that it was integral to this process. These findings reveal that non-spatial information about stimulus features is integrated into oculomotor
programs spatially represented in the SC, whose close proximity to the pre-motor circuit eliminates the need for distinct visual salience and motor maps for regulating visual behavior.

The evidence presented in this paper for feature-based contextual modulation in the activity of SC sensory-motor neurons adds further support to the hypothesis that the SC instantiates the visual salience map postulated by models of visual search and selective attention (Cave and Wolfe, 1990; Findlay and Walker, 1999; Itti and Koch, 2000; Glimcher et al., 2005; Hamker, 2006). According to these models, the stimulus-driven outputs from individual feature maps, which can be instantiated by extrastriate cortical areas, are integrated with goal-directed signals into the visual salience map. Previous studies have shown how SC neurons have stimulus-driven visual responses to targets and distracters in their receptive fields and that their activity evolves to reflect the selection of saccade goals (McPeek and Keller, 2002). SC also has stimulus representations whose magnitudes are predictive of which stimulus will be selected as a saccade target (Shen and Paré, 2007). The present study extends these findings further by demonstrating how SC stimulus representations are not purely stimulus-driven but also modulated by recent history as well as by visual context in a fast and flexible way.

Although the activity on the visual salience map is thought to be non-selective to visual features, it can be seen as sensitive to features when reflecting the salience of stimuli in a search display. Indeed, feature-based contextual modulation has been demonstrated in the sensory-motor activity of neurons within cortical areas FEF and LIP. These previous findings are consistent with the between-session priming effects that we observed, because they primarily involved static goal-directed signals. In these studies, either the monkeys were highly experienced with the target feature of a feature search task over many sessions (FEF: Bichot et al., 1996) or the stimulus features retained the same relevance over an individual visual search session (FEF: Bichot and Schall, 1999b; see also Bichot et al., 2001; LIP: Toth and Assad, 2002; Sereno and Amador, 2006). Such neuronal activity modulation, however, also reflects past trial history rather than
current trial demands, which underlie the feature-based contextual modulation we observed in the variable distracter-ratio search task. Moreover, when we took into account the effects of feature-based priming in the balanced displays, we still found a relationship between behavior and neuronal modulation. What remained could be due to additional goal-directed signals, which could include individual monkeys’ preferences or other internal states. The most closely related observation to ours is the feature-based modulation in sensory responses of neurons in visual cortex reported by Bichot and colleagues (2005). In this study, monkeys were cued with the target’s feature during the initial fixation period of each trial and were free to move their eyes to search a conjunction search display. During the ensuing search fixations, the activity of V4 neurons was enhanced whenever a preferred stimulus in their receptive fields matched the target’s feature. Similar neuronal activity modulation has also been observed in V4 (Motter, 1994a, b) and MT (Treue and Martinez-Trujillo, 1999) when monkeys were instructed to allocate their attention to different features in tasks precluding eye movements. Such enhanced neuronal activity has been presented as a neural correlate of feature-based attention – the ability to preferentially process certain features of visual objects irrespective of their locations.

The feature-based contextual modulation observed in our study might be analogous to that observed in attention studies. This is a reasonable suggestion given that the expression of feature-based attentional effects have been estimated to be within the latency range of the saccades made by our animals (~150 ms after instruction; Motter, 1994a). In the variable distracter-ratio search task, it is the search display itself that would provide the information about the feature for which to allocate attentional resources. Is there enough time to process this information before the SC activity modulation? This is highly possible given that our monkeys had considerable experience with these search displays. In addition, there is evidence that color can be discriminated within 50 ms (Verghese and Nakayama, 1994; Bodelon et al., 2007) and that the feed-forward sweep of visual processing is sufficient for extracting the gist of complex visual
scenes (Schyns and Oliva, 1994; Castelhano and Henderson, 2008). If the non-spatial contextual modulation in SC neuronal activity were taken to reflect feature-based attention, our results would provide unequivocal evidence that attention is at play within this sub-cortical structure, thus complementing existing evidence obtained in studies of spatial attention (Kojima et al., 1996; Ignashchenkova et al., 2004; see also Kustov and Robinson, 1996; Cavanaugh and Wurtz, 2004; Müller et al., 2005), in which shifts of attention could possibly be confounded by changes in motor preparatory activity.

Possible mechanisms for a fast and flexible modulation of stimulus representations by visual context are incorporated in existing models via interactions within feature maps (Cave and Wolfe, 1990; Itti and Koch, 2000; Hamker, 2006). According to these models, the unbalanced distracter composition in a visual search display would suffice to enhance the representations of the fewer distracters, thereby making them and the search target the primary representations competing for selection at the level of the salience map. Such low-level mechanisms, however, would entail changes in activity occurring much earlier than those we observed, perhaps as early as 20 ms following the onset of the visually evoked responses as when visual cortex neurons are activated by pop-out stimuli (Knierim and van Essen, 1992; Nothdurft et al., 1999, 2000; Burrows and Moore, 2009). Furthermore, these early changes in activity may be relatively small and perhaps only manifest in individual feature maps, i.e., not at the level of the visual salience map. Our observations that the stimulus feature sensitivity of SC neurons arose around 70 ms after the onset of their visually evoked responses and that the magnitude of those responses did not vary with stimulus salience argue against a purely stimulus-driven account. Rather, the timing of this modulation compares well with the timing of contextual effects in figure-ground segregation and curve tracing tasks (~70-90 ms), which have been argued to result from cortico-cortical recurrent processing (Zipser et al., 1996; Lamme et al., 1999; Supèr et al., 2001; Khayat et al., 2006; Khayat et al., 2009). In addition, it nearly coincided with the timing of saccade target selection,
which is thought to involve sensory-motor neurons instantiating the visual salience map. Whichever mechanism underlies the SC stimulus feature sensitivity we observed, our findings suggest that stimuli sharing a feature with the search target can be processed preferentially when they appear to belong to small perceptual group (Duncan, 1995), and it may be that stimulus-driven inputs to the salience map must be enhanced by goal-directed signals about the target’s identity for perceptual grouping to happen.

Early descriptions of the visual salience map considered it to be the last processing stage whose output feeds perception itself, but more recent work on visual search has its output specifying the next saccade target. How then is the salience map connected to the eye movement system if the SC is a node within the distributed network that forms the visual salience map? The common view in both conceptual (Glimcher et al., 2005) and formal computational models (Beck et al., 2008; see also Hamker, 2006) is that the SC is only a motor map reading out the end product of the selection process within a cortical salience map. Our findings, however, strongly suggest that there is no need for a motor map for saccades distinct from the salience map (see also Findlay and Walker, 1999). Visual and cognitive processing has long been observed in the activity of SC neurons (Goldberg and Wurtz, 1972), and neurons with visually evoked responses and saccade-related activity – like those recorded in this study – have been shown to project to the brainstem saccade generator circuit (Rodgers et al., 2006). With sufficient activation, potential saccade target representations in this structure can therefore become saccade programs via its direct access to the pre-motor circuits. This ability may also be conferred by the characteristic saccade-related, high-frequency burst of activity produced by SC neurons, which is significantly distinct from that observed in cortical neurons and the main candidate trigger signal for saccade initiation (Paré and Hanes, 2003).

Despite many similarities between the neuronal activity observed in FEF, area LIP and SC, it is unlikely that the visual salience map is simply replicated across these brain regions. With
respect to saccade target selection, we posit that this process results from the progressive filtering of distracter representations and amplifying of target representations from area LIP to FEF and onto SC. This is consistent with a recent comparative analysis showing that the reliability of the target/distracter discrimination improves from cortex to SC (Thomas and Paré, 2007). Contrary to the discrete target-selection/saccade-programming models mentioned above, this continuous flow of information between these brain regions could account for the discriminating activity observed simultaneously in cortex (Thompson et al., 1996; Thomas and Paré, 2007) and SC during visual search (McPeek and Keller, 2002; Shen and Paré, 2007) as well as the feature sensitivity in SC neuronal activity that we observed in this study.

The direct link between perceptual and motor processing suggested by our findings could be viewed as a substrate for the visual grasp reflex, the inflexible capture of overt attention by a salient visual stimulus (Hess et al., 1946; Theeuwes et al., 1998). The SC is indeed a phylogenetically old brain structure crucial to visual processing and orienting responses, but this does not imply that its visuo-motor function is inflexible. For instance, the anuran behaviors of prey catching and predator avoidance – which rest on the integrity of the optic tectum, the SC homologue in lower vertebrates – are modifiable (Ewert et al., 2001). Furthermore, some have argued that automatic sensory-motor activation is integral to, and not distinct from, voluntary behavior, which is regulated but not exclusively dictated by cortical circuits (Sumner and Husain, 2008). In conclusion, the SC may represent the primordial visual salience map for regulating gaze orienting behavior and it is unlikely that this function was entirely replaced by cortical areas in mammals. Instead, the cortical salience maps may confer more direct links to other behavior, e.g., visual perception and visuo-manual activities, in addition to their role in gaze orienting.
2.6 References


Chapter 3
Neural basis of saccade target retention
in superior colliculus during active vision
3.1 Introduction

The processes underlying active vision – such as the search for an object in a visual scene – include both the selection of the next object to examine and the retention of which objects have been examined so as to prevent their re-examination. This retention process is typically modeled as a perfect memory trace (Cave and Wolfe, 1990; Itti and Koch, 2000; Hamker, 2006), but human behavioral data suggest a more limited capacity (Horowitz and Wolfe, 1998; Gilehrizt and Harvey, 2000; McCarley et al., 2003). Our understanding of this important process in active vision is further limited by a lack of data about the underlying neural mechanisms. Here we estimated from the rate at which rhesus monkeys re-fixate visual stimuli when performing a multi-fixation visual search task that their retention ability is limited to no more than four objects and to last about 1 sec. Concurrent recording of the activity of superior colliculus (SC) sensory-motor neurons shows that the representations of stimuli in the search array already examined by the monkeys were significantly suppressed, though not eliminated, as compared to similar stimuli not yet examined. Given the contribution of SC to the visual salience map for eye movements (McPeek and Keller, 2002; Shen and Paré, 2007), these findings reveal how the representations on this map are dynamically updated from fixation-to-fixation, thus facilitating active vision.

3.2 Materials and Methods

Data were collected from four female rhesus monkeys (*Macaca mulatta*, 5-6.5 kg) cared for under experimental protocols approved by the Queen’s University Animal Care Committee and in accordance with the Canadian Council on Animal Care guidelines. The surgical procedure, data acquisition, and data analyses have been described previously (Shen and Paré, 2006, 2007). Behavioral data were collected from all four animals (N = 45), and we simultaneously recorded the extracellular activity of 37 SC neurons in two of those animals (M: 29; F: 8).
3.2.1 Behavioral paradigms

The main data of this report were collected using a grid conjunction search task. For each trial in this task, monkeys fixated on a fixation stimulus that acted as a cue for the target. This fixation stimulus could randomly appear in any of the 16 possible positions for the subsequent grid display (Fig. 3.1). Once fixated for 500-800 ms, the fixation stimulus disappeared followed by a gap period of 200 ms during which there was no visual stimulation but the animal was required to maintain fixation within a defined window. The search display then appeared, consisting of 16 stimuli that were conjunctions of a color (yellow: CIE x = 0.43, CIE y = 0.48 or green: CIE x = 0.29, CIE y = 0.60) and a shape (circle or square). The target stimulus was a unique combination of these features, and distracter stimuli could share either a feature with the target (same-color or same-shape) or have no feature in common with the target (opposite). The distracter types appeared in equal proportions (i.e., five each). The stimuli were matched for luminance (20 cd/m²) using a Minolta CS-100 Plus photometer and presented on a black background (<0.01 cd/m²). Monkeys were given 500 ms after stimulus presentation to make their first gaze fixation and were given an additional 5,000 ms for subsequent fixations if this initial fixation was not on the target. Monkeys were required to fixate the target for 500 ms to receive a liquid reward. The search target remained the same within each experimental session but changed across sessions. For sessions in which only behavioral data was collected, the stimuli were each 1° in diameter and were spaced 10° apart horizontally. For sessions in which neural data was also collected, the stimuli were arranged such that their spacing was determined by the vector of the neuron’s receptive field (RF). In other words, the array was positioned so that a stimulus fell in the neuron’s RF on nearly all fixations. The stimulus dimensions were then scaled with the eccentricity of the RF and in proportion to striate cortex receptive field magnification (Van Essen et al., 1984). The spacing between stimuli in these sessions ranged from 4.5° to 13° (mean: 7.9 ± 0.4°).
Figure 3.1 Grid conjunction search task.
Example trial progression and fixation sequence. Each trial began with the monkey fixating on a fixation stimulus that acted as a cue for the target. Following fixation, a gap period was provided during which the monkey had to maintain fixation. When the stimulus array was presented, monkeys freely searched for a unique target amongst 15 distracters, and were rewarded only after they fixated the target stimulus. On each trial, the fixation stimulus could appear randomly at any of the 16 possible stimulus locations. During neuronal recording sessions, the grid array was positioned such that a stimulus fell in the neuron’s RF on nearly all fixations.
Each conjunction search session was preceded by a **grid detection task** that served to familiarize the monkey with the target for that session. Trials in this task proceeded like those in the search task, but on array presentation only the target stimulus appeared (with no distracters) and monkeys were rewarded for fixating the single target stimulus within 500 ms of presentation. During neuronal recording sessions, data from this detection task were also used to map the neurons’ RFs. A **delayed saccade task** was also used in these sessions to characterize neurons by temporally dissociating visual stimulation from saccade execution (Paré and Wurtz, 2001).

### 3.2.2 Data analysis

The probability of re-fixation was calculated from all sessions by taking the total number of re-fixations after a given number of intervening fixations and dividing by the total number of trials having fixation sequence length equal to the number of intervening fixations.

SC neuronal activity related to distracters during the conjunction search task was analyzed in two conditions: distracters not yet examined vs. distracters previously examined (see Figure 3). The onset of fixation was concomitant to the distracter of interest falling in the neuron’s RF. The RF was delimited using visual stimulation and its center defined by the maximum visually evoked response. Offline, stimuli were treated as being within the RF if they evoked greater than half of the maximum response. For some neurons, the RF could then encompass two stimuli. Fixations were only included if both the preceding and proceeding saccades were made away from the neuron’s RF (five or fewer opposing directions, depending on how broadly tuned the neurons were) and if its duration was ≥100ms. To be included in the previously examined condition, the distracter of interest must have been fixated no more than four fixations ago, as determined by the behavioral data (see Fig. 3.2).

We quantified the modulation of responses to each distracter type across the neuronal sample by calculating a modulation index every 5 ms, where $$MI = (\text{Previously Examined} - \text{Not Previously Examined}) / \text{Previously Examined}$$.
Yet Examined) / (Previously Examined + Not Yet Examined). Positive values would indicate an enhancement of the previously examined distracter activity, while negative values indicate a suppression of the previously examined distracter activity. To determine whether the MI was significantly different from 0, a permutation test (10,000 iterations) of the MI distribution was performed for each distracter type over time. Only neurons having at least 5 fixations in each condition were included in these analyses, therefore resulting in different subsets of neurons contributing to the different distracter type analyses (same-color: N = 35; same-shape: N = 35; opposite: N = 32). In addition, neurons were included for analysis only if they had distracter-related activity (> 1 sp/s) in the first 100 ms from fixation onset in the ‘not yet examined’ condition. The average distracter-related activity during that time was 33 ± 5, 28 ± 5, and 26 ± 5 sp/s for same-color, same-shape, and opposite distracters, respectively.

We used the data collected in the delayed saccade task to calculate a visuo-movement index (VMI; Shen and Paré, 2007; Thomas and Paré, 2007), which quantified the relative magnitude of visually evoked and saccade related activity of each neuron: $VMI = (vis – mov)/(vis + mov)$, where $vis$ is the mean discharge rate over the first 100 ms following stimulus presentation and $mov$ is the peak discharge rate within ± 40 ms of saccade onset.

3.3 Results

We first investigated the retention process involved in active vision by examining the distribution of gaze fixations as a function of time in a visual search task. Monkeys searched freely for a unique conjunction target embedded among distracter stimuli (Fig. 3.1; see Materials and Methods), performing a total of 31,625 trials. This difficult task promoted the occurrence of sequences of multiple gaze fixations. Only 27% of trials were successfully completed with a single new fixation. On average, monkeys made 2.8 ± 0.2 fixations before foveating the search target. The low probability of re-fixations (4.4%) that we observed is evidence that the monkeys
retained the objects they had already examined. Figure 3.2 shows how the probability to re-fixate a distracter for each monkey varied as a function of the number of intervening fixations. Perfect retention predicts a zero probability of re-fixation, while no retention predicts chance probability (Gilchrist and Harvey, 2000). We found that the probability of re-fixation was significantly less than chance \( p < 0.05, \chi^2 \) test only for the first 3-4 intervening fixations. Naturally, the time until re-fixation also increased with the number of intervening fixations (Fig. 3.2), but this time overlapped significantly across intervening fixation bins, making a discrete time-based analysis of these data impossible to conduct. In general, 3-4 intervening fixations were completed after approximately 700-1200 ms. Certainly, both the passing of time and the number of items examined are factors determining retention ability.

Theories of visual search posit that sensory (bottom-up) inputs and goal-directed (top-down) signals are combined into representations on a visual salience map. The representations on this salience map compete to select the next object to process or the next object to look at in the case of active vision (Cave and Wolfe, 1990; Findlay and Walker, 1999; Itti and Koch, 2000; Hamker, 2006). The probability of selection is dictated by the relative strengths of these representations, and we therefore hypothesize that the representations of objects that were already examined are temporarily suppressed. To test this hypothesis, we recorded sensory-motor neurons while two of the monkeys (\( M \) and \( F \)) performed the visual search task described above. The visual salience map for eye movements is instantiated by a neural network distributed across several brain regions, including the lateral intraparietal (LIP) area within the posterior parietal cortex (Colby and Goldberg, 1999), the frontal eye field (FEF) within the prefrontal cortex (Thompson and Bichot, 2005), and the superior colliculus (SC) in the midbrain (Shen and Paré, 2007). We chose to record neurons within the SC, because this structure directs motor outputs to the saccade generating system (Rodgers et al., 2006) and its neuronal activity can therefore more
Figure 3.2 Retention of recently examined items.
Probability of re-fixation as a function of the number of intervening fixations (left ordinate axis and black bars). All four animals showed probabilities of re-fixating a recently examined stimulus significantly lower than chance (1/15 or 0.067) for the first three or four intervening fixations (closed bars; p < 0.05, $\chi^2$ tests). Error bars: 95% CI. Median duration until re-fixation as a function of the number of intervening fixations (right ordinate axis and gray points). Error bars: 10th and 90th percentiles; those extending beyond the scale of the figure have been cropped. Overall, the occurrence of a re-fixation was rare, representing only a small percentage of total trials (M: 1.4%, F: 2.7, G: 8.3%, H: 5.2%).
closely impact saccade target selection.

Previous studies on saccade target selection in visual search tasks have shown that SC neuronal activity associated with the search target becomes enhanced while that associated with a distracter becomes suppressed in advance of the first targeting saccade made in response to the search display (McPeek and Keller, 2002; Shen and Paré, 2007). All 37 neurons recorded in this study also reflected this discrimination process, on average, 63 ± 4 ms before the onset of saccades made in trials in which the search target was foveated with a single fixation. We compared the activity related to distracters that had been examined within the retention interval (i.e., with less than or equal to three intervening fixations) to that related to distracters that had not yet been examined (see Fig. 3.3). Since monkeys were more likely to fixate a distracter that shared a feature with the target and SC neuronal activity varied for each distracter type (Fig. 3.4), each distracter type was treated independently to control for any effects of target-distracter similarity (see also Bichot and Schall, 1999). Figure 3.3 illustrates how, for one example neuron, the activity related to a previously examined same-color distracter is suppressed compared to that for a same-color distracter not yet examined. To determine the extent of such suppressive effects across the neuronal sample, we computed a modulation index that contrasted the two conditions over time (see Materials and Methods). Negative values of this index indicate that the activity associated with a previously examined same-color distracter was less than that for those not yet examined. Figure 3.5 shows how the modulation index for same-color distracters was significantly negative following the onset of fixation and until the proceeding saccades (p < 0.001, N = 35, permutation test) but still greater than the baseline index (i.e., maximal suppression, p < 0.001). Results were similar for same-shape (p < 0.001, N = 35) and opposite distracters (p < 0.001, N = 32; see Fig. 3.6). These suppressed representations were ~40-50% of the representations of not yet examined objects.
Figure 3.3 Suppressed activity for previously examined items
Same-color distracter-related activity during fixations after the first saccade for an example neuron. The analysis of neuronal activity during this task involved two conditions: 1) when a distracter stimulus that had not yet been examined in the current sequence of fixations fell in the neuron’s RF (red); and 2) when a previously examined distracter stimulus fell in the neuron’s RF (blue). For both conditions, the preceding and proceeding saccades of that particular fixation were both away from the neuron’s RF. Baseline activity during the delayed saccade task as determined from a 100-ms epoch before stimulus onset is indicated by the gray dashed line.
Figure 3.4 Distracter type influences both SC activity and behavior.
The probability of fixating each distracter type varies with SC distracter related activity. This relationship was not significant, however, due to the large variability in distracter related activities. Average (± SE) distracter fixation probability (same-color: 0.76 ± 0.02; same-shape: 0.16 ± 0.02; opposite: 0.08 ± 0.01) as a function of distracter activity (same-color: 35 ± 5 sp/s; same-shape: 28 ± 4 sp/s; opposite: 26 ± 4 sp/s) during a 50-ms epoch starting 50 ms after fixation onset.
**Figure 3.5 SC neurons reflect visual search retention**

Population modulation index (MI: mean ± SE; left ordinate axis) for same-color distracters. Dashed gray line at 0 indicates hypothetical MI if there was no suppression, while dashed gray curve (± SE) indicates hypothetical MI if there was maximal suppression (i.e., suppression to the neuron’s baseline activity). Modulation ratio (% change) is shown on the right ordinate axis. Open circles indicate the mean fixation duration for each neuron (i.e., onset of eye movements away from neurons’ RFs).
Figure 3.6 SC neuronal activity reflects visual search retention
Population modulation index (MI; mean ± SE; left ordinate axis) for same-shape (left) and opposite (right) distracters. Dashed gray line at 0 indicates hypothetical MI if there was no suppression, while dashed gray curve (± SE) indicates hypothetical MI if there was maximal suppression (i.e., suppression to baseline). Modulation ratio (% change) is shown on the right ordinate axis. Open circles indicate the mean fixation duration for each neuron (i.e., onset of eye movements away from neurons’ RFs).
Visual processing during a fixation is not limited to information available at the fovea, but also extends to information from the periphery (Levy-Schoen, 1981; Bertera and Rayner, 2000). The extra-foveal processing of some distracters on each fixation could therefore have contributed to the additional suppression of peripheral distracter representations. Such representations contribute in part to the control condition (‘distracters not yet examined’), and it is therefore reasonable to assume that our measure of suppression is conservative.

We also determined whether an individual neuron’s ability to suppress a previously examined representation was related to its discharge characteristics. A neuron’s average MI for same-color distracters calculated between 50 and 100 ms following fixation onset was not related to its position along the visuo-movement index (p = 0.26, Pearson correlation), its visually evoked response (p = 0.38), or its peak saccade activity (p = 0.74). Moreover, a neuron’s discharge rate during the delay period in the visually- and memory-guided saccade tasks was also not predictive of its ability to suppress previously examined representations (p = 0.83 and p = 0.77, respectively). Data were not different for same-shape or opposite distracters.

If the monkeys employed a methodical scanning strategy to find the target rather than searching actively, the suppressed representations would then reflect not the retention of already examined objects but their prospective selection as saccade targets. To assess whether direction-based strategies were used, we examined the distribution of saccades to each of four directions (up, down, left, right) for each neuronal recording session. If a raster-like scanning strategy were used, we should find peaks in the distribution suggesting a bias towards certain (e.g., up-down or right-left) directions (Findlay and Brown, 2006; Gilchrist and Harvey, 2006). We considered search arrays that were presented in a horizontal-vertical orientation separately from those presented along the diagonal to account for any differences in array presentation. Saccades were distributed evenly in all four directions for both types of presentation, with the probability of saccade direction not being different from expected (chance: 0.25; p > 0.0125, repeated t tests;
horizontal-vertical: mean probability: 0.25 ± 0.01, N = 17; diagonal: 0.25 ± 0.01, N = 20). It is unlikely, then, that monkeys adopted a systematic scanning strategy in our task.

The suppression in object representations that we observed in SC neuronal activity could be taken to reflect a short-lived, selective suppression in saccade processing. Such a mechanism to prevent re-examination has been suggested by the observation that fixations preceding saccades made back to the previously fixated object are significantly longer than those preceding saccades made in other directions (Hooge and Frens, 2000). A possible neural substrate is the push-pull interaction across the SC map suggested by the observation that a neuron’s activity is momentarily suppressed following the presentation of stimuli located diametrically opposite to its receptive field (Dorris et al., 2007). To determine whether an inhibition-of-saccade-return mechanism contributed to the suppressed activation in our study, we tested whether the activation associated with just-examined objects (i.e., one intervening fixation) differed from that associated with objects examined 2-3 fixations ago (Fig. 3.7). The inhibition-of-saccade-return hypothesis predicts that the representation of a just-examined object would be more suppressed than one after 2-3 intervening fixations. We found no significant difference in suppression between these two conditions (p > 0.05, permutation test; see Fig. 3.7). Moreover, we found that the fixation before a return saccade in our task (1 intervening fixation) was not significantly longer than the preceding fixation (157 ± 4 vs. 162 ± 5 ms; p = 0.35, paired t-test). These data also show that the re-fixation of a stimulus did not occur because the original fixation was too short, which would indicate that monkeys had failed to fully process the visual stimulus. Taken together, these results suggest that most of the suppression we observed was not due to a short-lived, selective suppression in saccade processing. Given the behavioral results of this study, one would predict that the activity associated with distracters examined more than four fixations ago would no longer be suppressed. Unfortunately, the limited number of fixations per trial and the relatively
Figure 3.7 Suppressed representations do not reflect inhibition-of-saccade-return.

A, Schematic showing an example of a fixation that would be included in the just-examined same-color distracter condition (top) and one that would be included in the 2- or 3-intervening fixations condition (bottom). B, Modulation index (MI; mean ± SE) for same-color distracters, where MI = (Just examined – 2+Intervening Fixations) / (Just examined + 2+Intervening Fixations). Dashed gray line at 0 indicates hypothetical MI if there was no difference between the two conditions. MI was significantly different from 0 only at 5 ms after fixation onset (p < 0.05, permutation test). Open circles indicate the mean fixation duration for each neuron (i.e., onset of eye movements away from neurons’ RFs). Only neurons having five or more fixations to contribute to each condition were analyzed (N = 15). There were not sufficient data to analyze same-shape or opposite distracters.
low probability that an examined distracter falls in a neuron’s receptive field prevented us from testing this prediction with this data set.

3.4 Discussion

In addition to the gradual suppression of distracter-related activity during the process of saccade target selection in visual search tasks, the suppression of representations on the salience map has previously been observed in a variety of tasks, whereby activity associated with stimuli that are currently not selected as saccade targets (e.g., Glimcher and Sparks, 1992; Paré and Wurtz, 2001), systematically ignored (Ipata et al., 2006; Mirpour et al., 2009), and associated with reduced or no expected reward (Dorris and Munoz, 1998; Dorris and Glimcher, 2004; Mirpour et al., 2009) is persistently reduced. Here we showed how, in ongoing visual search, representations of examined objects are also suppressed, thereby lowering the probability of them being selected again as a saccade target. This suppression parallels the monkeys’ ability to temporarily retain about three objects at a time during visual search as well as that of humans performing visual search tasks (Gilchrist and Harvey, 2000; McCarley et al., 2003; see also Peterson et al., 2001; Beck et al., 2006b; Geyer et al., 2007). Some studies (Peterson et al., 2001; Motter and Holsapple, 2007) have reported very high retention capacities, but such results may be in part due to extra-foveal processing of stimuli in dense arrays (McCarley et al., 2003; see also Beck et al., 2006a).

One mechanism commonly used in theoretical models of visual search to prevent the re-fixation of previously examined items is labeled inhibition of return (IOR; Cave and Wolfe, 1990; Itti and Koch, 2000; Hamker, 2006). In these models, once an item has been fixated it is eliminated from the pool of potential saccade targets (i.e., sampling without replacement). The implementation of IOR in these models does not account fully for the behavioral data reported here and elsewhere (Gilchrist and Harvey, 2000; Peterson et al., 2001; McCarley et al., 2003), nor does it necessarily match previous empirical descriptions of IOR. IOR is a phenomenon first
identified by Posner and Cohen (1984) who described it as an increase in the latency of a response to a probe presented at a recently cued position as compared to the latencies of responses made elsewhere. IOR was then proposed to encourage orienting toward novel items. Whether this increase in response latency is limited to the most recently cued position has been debated (Pratt and Abrams, 1995; Tipper et al., 1996) and perhaps not unequivocally resolved (Abrams and Pratt, 1996; Danziger et al., 1998; Snyder and Kingstone, 2001). One key difficulty in resolving this issue is that it is not known whether attention is always deployed to the cues used in these experiments. Klein (1988) suggested that IOR might be related to the retention process that is thought to help visual search (the foraging-facilitator hypothesis) after showing a decrease in response latencies to a probe presented at previous stimulus locations following covert visual search trials. IOR has since been investigated in overt visual search studies by determining saccade latencies to probes presented at recently examined items in a visual scene. Results from these studies indicate that the increase in saccade latency occurs for probes presented at the location examined one fixation ago (Klein and MacInnes, 1999; MacInnes and Klein, 2003; Thomas et al., 2006) as well as two fixations ago (Klein and MacInnes, 1999; Thomas et al., 2006; Dodd et al., 2009). The existence of this slowing effect past two fixations, however, has been inconsistently reported (Thomas et al., 2006; Dodd et al., 2009).

It remains difficult to relate IOR to the retention process involved in active vision because this phenomenon is studied by measuring the latency of saccades made in response to probes that are not search items (but see Handy et al., 1999), whereas the retention of one search item is measured by calculating the probability of it being re-fixated. One would think that a large IOR should correspond to a low probability of re-fixation. However, the opposite relationship has been reported by the one study (Hooge et al., 2005) that tested this hypothesis, with fixation duration as a measure of IOR. In our study, the low probability of re-fixation for the item most recently examined was also not associated with shorter fixation durations. Lastly, monkey studies
of IOR showed cue-induced suppression in the visually evoked responses of SC neurons, which was correlated with an increase in response time (Dorris et al., 2002). Because of the repeated visual stimulation in this task, it is, however, not clear whether this suppressed activity reflects anything else other than sensory habituation. Further experiments are necessary for a definitive answer regarding the relationship between the retention process involved in active vision and IOR, which remains a phenomenon far from being completely understood.

An alternative hypothesis is that visual working memory underlies the retention process in active vision. Neuroimaging studies have suggested that visual search and visual working memory share a common neural architecture (Awh and Jonides, 2001; see also Emrich et al., 2009; Anderson et al., 2010). Reports of interference from search tasks on visual working memory performance in dual-task paradigms (Oh and Kim, 2004; Woodman and Luck, 2004) further suggest that these tasks may compete for common limited resources. Such dual-task paradigms have demonstrated both facilitative (Williams et al., 2005; Woodman et al., 2007) and inhibitory (see also Downing and Dodds, 2004; Woodman et al., 2007) effects of working memory on visual attention. Notably, human studies of visual working memory with sequential comparison tasks suggest that it is severely degraded when loaded with more than four items (Vogel and Awh, 2008). These previous studies suggest that visual working memory is a flexible process that facilitates visual search by maintaining information about both the search target and the items already examined.

Many neurons within the network that instantiates the visual salience map also display persistent delay activity following the removal of the visual stimulus in delayed response tasks (Bruce and Goldberg, 1985; Gnadt and Andersen, 1988; Funahashi et al., 1989; Glimcher and Sparks, 1992; Munoz and Wurtz, 1995; Paré and Wurtz, 2001; Sommer and Wurtz, 2001). It is interesting to note the similarity of these observations with the persistent suppression that we observed throughout the fixation period (see Figs. 3.3 and 3.5-3.6). In addition, suppressed
representations in posterior parietal (Paré and Wurtz, 2001), prefrontal (Miller et al., 1996; Sommer and Wurtz, 2001; Hasegawa et al., 2004; Johnston and Everling, 2009) and temporal cortices (Miller et al., 1991; Riches et al., 1991; Chelazzi et al., 1998) have been reported in visual memory tasks. Interestingly, these modulatory effects could last for at least three intervening stimulus presentations (Miller et al., 1991; see also Riches et al., 1991). This network therefore sustains mnemonic representations that could guide behavior by helping either the selection of objects for processing or the filtering of already processed objects. How these mnemonic representations enhance or suppress a representation at the level of the visual salience map might be conferred by their anatomical connections (e.g., Johnston and Everling, 2006).

In conclusion, our findings suggest that objects recently examined during a visual search are prevented from being selected for re-examination owing to their representations on the visual salience map being suppressed. This resource-limited retention process may correspond to visual working memory, instead of transient inhibition in attentional and saccade processing.
3.5 References


Chapter 4
Predictive saccade target selection
in superior colliculus during visual search
4.1 Abstract

Searching for a visual object naturally involves sequences of gaze fixations, during which the current foveal image is analyzed and the next object to inspect is selected as the next saccade target. The observation that fixation durations are short in such sequences has been taken as evidence of concurrent saccade processing. This additionally suggests that the selection of the saccade target could occur before the fixation just preceding the acquisition of the target. To test this hypothesis, we recorded the activity of sensory-motor neurons in the midbrain superior colliculus (SC) while two female rhesus monkeys (Macaca mulatta) performed a visual conjunction search task. In this task, monkeys generally made multiple fixations before foveating the target. Fixation durations were significantly shorter than the latency of the initial responses to the search display, with about one quarter being shorter than the shortest response latencies. The time at which SC sensory-motor activity discriminated the target from distracters occurred significantly earlier for the selection of subsequent fixations than for the selection of the first fixation. It even occurred before the visual afferent delay in over half of the neuronal sample, suggesting that the process of selection can encompass at least two future saccade targets. This predictive selection was present even when differences in saccade latencies were taken into account. Altogether, these findings demonstrate how neural representations on the visual salience map are processed in parallel, thus facilitating visual search.
4.2 Introduction

Primates naturally explore the visual environment using sequences of gaze fixations that are interrupted intermittently by saccadic eye movements. During these fixations, the foveal image is analyzed and the next saccade target is selected. The visual search paradigm has been a valuable approach to studying this visual behavior and the underlying process of saccade target selection. The neural signature of the selection process has been successfully investigated in neurons in the lateral intraparietal area (LIP), frontal eye fields (FEF) and the superior colliculus (SC). Neurons in these brain regions are thought to instantiate the visual salience map, whose representations of visual stimuli compete for selection. These neurons respond to the presence of visual stimuli in their receptive fields, with activity that is initially indiscriminate but evolves to indicate the location of the target before saccade initiation (LIP: Ipata et al., 2006; Thomas and Paré, 2007; FEF: Thompson et al., 1996; Thompson et al., 2005; SC: McPeek and Keller, 2002a; Shen and Paré, 2007). This account is limited, however, to the selection of the first saccade target following the presentation of the search display (but see Murthy et al., 2007).

More difficult visual search tasks have been shown to promote the occurrence of multiple fixations before the search target is found (Motter and Belky, 1998a, b; Shen and Paré, 2006, 2007; Nothdurft et al., 2009). When combined with neuronal recordings, such tasks could inform us about how saccade targets are selected from time-varying representations on the visual salience map during sequences of fixations (Bichot et al., 2005). From the analyses of sequences of fixations, the most significant observation has been that the durations of the fixations following the initial saccade response to the search display presentation are shorter than the latency of that initial response (Viviani and Swensson, 1982; Hooge and Erkelens, 1996; Theeuwes et al., 1998; McPeek et al., 2000; McPeek and Keller, 2001). As such, this observation suggests that there is
concurrent saccade processing, which also implies that the process of selecting the next saccade target could occur before the fixation just preceding the acquisition of that target.

In this study, we tested this hypothesis by recording the activity of SC sensory-motor neurons while monkeys performed a visual search task. The target was a unique conjunction of features presented in a grid array with multiple distracters, some of which shared a feature with the search target.

4.3 Materials and Methods

Data were collected from four female rhesus monkeys (Macaca mulatta, 5-6.5 kg, 6-10 years old) cared for under experimental protocols approved by the Queen’s University Animal Care Committee and in accordance with the Canadian Council on Animal Care guidelines. During the post-surgical recovery period, animals received both antibiotics and analgesic medications. The surgical procedure, stimulus presentation, data acquisition, and data analyses have been described previously (Shen and Paré, 2006, 2007). Behavioral data were collected from all four animals (F: 8; M: 24; G: 4; H: 4), and we simultaneously recorded the extracellular activity of 32 SC neurons in two of those animals (monkeys M and F).

4.3.1 Behavioral paradigms

The main data of this report were collected using a grid conjunction search task. On each trial, monkeys fixated on a fixation stimulus that acted as a cue for the target. This fixation stimulus could randomly appear in any of the 16 possible positions for the subsequent grid display (Fig. 4.1). Once fixated for 500-800 ms, the fixation stimulus disappeared followed by a gap period of 200 ms during which there was no visual stimulation but the animal was required to maintain fixation within a defined window. The search display then appeared, consisting of 16 stimuli that were conjunctions of a color (yellow: CIE \( x = 0.43 \), CIE \( y = 0.48 \) or green: CIE \( x = \))
Figure 4.1 Grid conjunction search task
Trial progression and example fixation sequence. Each trial began with the monkey fixating on a fixation stimulus that acted as a cue for the target. Following fixation, a gap period was provided during which the monkey had to maintain fixation. When the stimulus array was presented, monkeys were free to search for the unique target amongst 15 distracters, and were rewarded only after they fixated the target. On each trial, the fixation stimulus could appear randomly at any of the 16 possible stimulus locations.
0.29, CIE $y = 0.60$ and a shape (circle or square). The single target stimulus was a unique combination of these features, with distracter stimuli that could share either a feature with the target (same-color or same-shape) or have no feature in common with the target (opposite). The distracter types appeared in equal proportions (i.e., five each). The stimuli were matched for luminance (20 cd/m$^2$) using a Minolta CS-100 Plus photometer and presented on a black background (<0.01 cd/m$^2$). Monkeys were given 500 ms after the presentation of the search display to make their first gaze fixation and were given an additional 5,000 ms for subsequent fixations if this initial fixation was not on the target. Monkeys were required to fixate the target for 500 ms to receive a liquid reward. The search target remained the same within each experimental session but changed across sessions. For sessions in which only behavioral data were collected, the stimuli were each 1° in diameter and were spaced 10° apart horizontally and vertically. For sessions in which neuronal activity was also recorded, the stimuli were arranged such that their spacing was determined by the vector of the neuron’s receptive field (RF). In other words, the array was positioned so as to maximize the probability that a stimulus fell in the neuron’s RF on each fixation. The stimulus dimensions were then scaled with the eccentricity of the RF and in proportion to striate cortex receptive field magnification (Van Essen et al., 1984).

Each conjunction search session was preceded by a grid detection task that served to familiarize the monkey with the target for that session and, for neuronal recording sessions, to characterize the extent of the neuron’s RF. Trials in this task proceeded as those in the search task, but on display presentation only the target stimulus appeared (with no distracters) and monkeys were rewarded for fixating the single target stimulus within 500 ms of presentation.

In recording sessions, the responses of neurons were first characterized while monkeys performed a delayed saccade task to temporally dissociate visual stimulation from saccade execution (Paré and Wurtz, 2001).
4.3.2 Data analysis

Methods for neuronal data analysis have been previously described (Thompson et al., 1996; Shen and Paré, 2007; Thomas and Paré, 2007). Briefly, neuronal activity was quantified as continuously varying spike density functions aligned on the onset of the visual stimulus presentation (stimulus-aligned), fixations following the first saccade (fixation-aligned) or saccades (saccade-aligned). Spike density functions were constructed by convolving spike trains with a combination of growth (1-ms time constant) and decay (20-ms time constant) exponential functions that resembled a postsynaptic potential (Thompson et al., 1996).

We used Signal Detection Theory to quantify the process of saccade target selection in our search task (see Thompson et al., 1996; Shen and Paré, 2007; Thomas and Paré, 2007). This method estimates how well an ideal observer of SC activity can discriminate between the activity related to a target falling in the neuron’s RF and that related to a distracter in the neuron’s RF. Receiver operating characteristic (ROC) curves were calculated during successive 5-ms intervals and the area under each of those ROC curves was then plotted as a function of time and fit with a Weibull function to describe the time course of saccade target selection. The point at which the function reached a criterion value of 0.75 was taken as the neuron’s discrimination time, and the upper asymptote of the function was taken as the neuron’s discrimination magnitude. Best-fit functions were calculated only with activity occurring before the initiation of saccades, and calculations were terminated once there were fewer than five target or distracter trials. The ranges of saccade latencies in target and distracter trials were matched. The minimum saccade latency for this analysis was 90 ms. We also conducted successive rank-sum tests on the same 5-ms intervals used for the ROC analysis to determine whether target- and distracter-related activity were significantly different from each other (Thomas and Paré, 2007). Fixations were only included if the preceding saccades were made away from the neuron’s RF (five or fewer opposing
directions, depending on how broadly tuned the neurons were). To be included in any analysis, neurons had to contribute at least five target and five distracter trials.

We calculated a visuo-movement index (VMI; Shen and Paré, 2007; Thomas and Paré, 2007) with data collected in the delayed saccade task. This index quantifies the relative magnitude of visually evoked and saccade related activity of each neuron: \( VMI = (\text{vis} - \text{mov})/(\text{vis} + \text{mov}) \), where \( \text{vis} \) is the mean discharge rate over the first 100 ms following stimulus presentation and \( \text{mov} \) is the peak discharge rate within \( \pm 40 \) ms of saccade onset. Neurons with stronger visually evoked activity have VMIs closer to 1.0 and those with stronger saccade related activity have VMIs closer to \(-1.0\). The mean VMI value of the neuronal sample was \(-0.65 \pm 0.05\) (range = \(-0.99 \rightarrow 0.01\)).

4.4 Results

We collected data from four monkeys over 40 sessions of the grid conjunction search task for a total of 27,747 trials. Monkeys, on average, needed \(2.7 \pm 0.26\) (range: 1-14) fixations to acquire the search target in our task, and successfully did so with a single fixation in only 29.7% of trials. As the fixation stimulus could randomly appear in any of the 16 locations within the grid, the distance between the target and fixation stimuli could vary. As a result, the probability of acquiring the target after a single saccade was significantly greater when the target was located adjacent to the fixation stimulus than when it was further eccentric (\(0.31 \pm 0.01\) vs. \(0.26 \pm 0.01\), \(p < 0.01\), t test). These results suggest that stimuli were discriminable, but that discriminability decreased somewhat with eccentricity.

The time it took to respond to the initial presentation of the visual search display (response time, RT) was not different for trials in which monkeys made a single new fixation as compared to trials in which they made a sequence of multiple fixations (\(188 \pm 3\) vs. \(184 \pm 2\) ms; \(p = 0.23\), t test). RT in multiple fixation trials was significantly longer than the durations of the subsequent
fixations in all four animals (Fig. 4.2A; p < 0.001, t test). Figure 4.2B shows how in a single session for one animal (monkey F) this effect was due to a proportion (25%) of fixation durations that were shorter than the shortest RT. This was also the case for the other monkeys: On average, 26 ± 2% (F: 36%, M: 19%, G: 32%, H: 45%) of subsequent fixations had durations shorter than the shortest initial RT, which was on average 116 ± 2 ms (Fig. 4.2C). These data suggest that the process of saccade target selection can occur in parallel for at least two saccade targets.

To determine whether this parallel selection occurs at the level of the visual salience map, we simultaneously recorded the activity of single sensory-motor neurons in the SC intermediate layers during 32 grid search sessions in two monkeys. We quantified the process of saccade target selection using Signal Detection Theory (see Materials and Methods) and determined the discrimination probability over time with data aligned to stimulus (search array) onset. All neurons discriminated the target from distracters before saccades were made. On average, discrimination time (DT) occurred 139 ± 3 ms (range: 106-174 ms) after the onset of the search display and discrimination magnitude (DM) was 0.94 ± 0.01 (range: 0.79-1) for trials in which the target was acquired with a single fixation. To examine the process of saccade target selection during subsequent fixations, we compared these single-fixation trials to ones in which the monkey made multiple fixations before acquiring the target (see Fig. 4.3A and 4.3B insets). Figure 4.3 illustrates this comparison for one example neuron. For trials in which the monkey correctly foveated the target after a single saccade, the neuron’s activity discriminated the target from distracters 118 ms after the search array onset (Fig. 4.3A). For trials in which the monkey made multiple fixations, discrimination occurred just 60 ms after the onset of the fixation that preceded target acquisition (Fig. 4.3B). DM, however, for both single and multiple fixation trials were similar and near perfect (~1). We quantified the saccade target selection process for the population of neurons we recorded by calculating the mean (± SE) discrimination probability.
Figure 4.2 Search task behavior

A, Average (± SE) initial response times (closed bars) and fixation durations (open bars) in multiple saccade trials for each monkey. * indicates p < 0.001. B, Example session data from monkey F. Initial response time (closed bars) and fixation duration (open bars) distributions for fixations on distracters. Minimum response time in this example session was 119 ms. C, Mean (± SE) proportion of total fixations with durations less than the minimum response time for each monkey. Range: F: 28-44%, M: 7-36%, G: 27-36%, H: 38-54%.
Figure 4.3 Example SC sensory-motor neuron activity in the grid conjunction search task. 
A, Saccade target selection in single fixation trials. top: Mean (± SE) activity for target (solid) and distracter (dashed) trials, aligned on the onset of the visual search display. The occurrence of saccades is indicated by the gray horizontal lines. bottom: Discrimination probability as a function of time. The areas under the ROC curve (+) were fit with a Weibull function and discrimination time (DT) was determined using an arbitrary criterion of 0.75. Discrimination magnitude (DM) was determined by the upper asymptote of the Weibull function. B, Saccade target selection in multiple fixation trials.
over time for both single and multiple fixation trials. The discrimination probability was already significantly greater at fixation onset for multiple fixation trials and remained that way until 145 ms following stimulus/fixation onset (Fig. 4.4A; p < 0.05, t tests), suggesting that the selection of a saccade target that was part of a sequence occurred earlier than the selection of a single saccade target. DT, as determined from individual Weibull fits (see Materials and Methods), was on average significantly shorter in multiple fixation trials (76 ± 6 ms) as compared to single fixation trials (139 ± 3 ms; p < 0.001, t test). This effect was not due to the shortest fixation durations in multiple fixation trials as only fixations with durations of >90 ms were used in this analysis. These results from the ideal observer analysis were additionally supported by an analysis of neuronal activity over time: In the single fixation condition, the earliest occurrence of significantly greater target than distracter activity was at 70 ms following the display onset, but over half (18/32, 56%) of the neurons had significantly greater (p < 0.05, rank sum test) target activity before the visual afferent delay (50 ms; Goldberg and Wurtz, 1972; McPeek and Keller, 2002a) and even before fixation onset in nearly 20% (6/32) of neurons in multiple saccade trials (Fig. 4.4A, bottom). Figure 4.5 depicts the normalized activity profile for all neurons. Note that the increase in activity around fixation onset occurs only for the stimulus that will become the next saccade goal. This was the case for both the subset of neurons with significant target-related activity before the visual afferent delay and the subset whose activity was modulated later (not shown).

To capture the time course differences between the two selection processes, we plotted the cumulative distributions of discrimination probabilities when the stimulus appeared in the neuron’s receptive field as well as 100 ms before and 100 ms after its appearance (Fig. 4.4A, right). Discrimination probabilities were not different between single and multiple fixation trials 100 ms before stimulus appearance (0.50 ± 0.01 vs. 0.52 ± 0.01; p = 0.51, t test) and were also
Figure 4.4 Predictive saccade target selection in SC

A. Mean (± SE) discrimination probability as a function of time, aligned to the onset of the search display. inset: proportion of neurons having significantly greater (p < 0.05, rank sum test) target-than distracter-related activity as a function of time. right: Cumulative distributions of discrimination probability at 100 ms prior to (top), at (middle) and 100 ms following stimulus/fixation onset (bottom). B, Data as in A, aligned to the onset of saccades. Black: single fixation trials, red: multiple fixation trials.
Figure 4.5 Predictive activity for saccade targets
Mean normalized activity profile for all neurons aligned to the onset of fixation just prior to target acquisition. Each neuron’s target- and distracter-related activity was normalized to its distracter-related activity at -100 ms before fixation onset.
not different from chance (p = 0.86 and p = 0.28, respectively), indicating that the early selection of a subsequent saccade target was not due to any differences in neuronal activity occurring during the previous fixation. The discrimination probability in single fixation trials was still not different from chance at stimulus appearance (0.49 ± 0.01; p = 0.41), while it was significantly greater than chance in multiple saccade trials at fixation onset (0.58 ± 0.01; p < 0.001). Finally, at 100 ms after stimulus appearance, discrimination probabilities in both single and multiple fixation trials were significantly greater than chance (p < 0.001), but those of the multiple fixation trials were still significantly greater than single fixation trials (0.80 ± 0.02 vs. 0.58 ± 0.02; p < 0.001).

It is possible that the shift towards an earlier selection process in multiple-fixation trials was driven mainly by fixations of very short duration (i.e., 50-100 ms). To account for this, we aligned the data to the onset of saccades, thereby eliminating any differences in timing between the single- and multiple-fixation trials. Discrimination probabilities were still significantly greater in multiple fixation trials up to 40 ms before saccades (Fig. 4.4B; p < 0.05, t tests). That the discrimination probabilities were not different just before saccades suggests that the neurons’ ability to discriminate the target stimulus from distracters did not change between the two conditions. McPeek and Keller (2002a) previously reported that the DT of some SC visuo-movement neurons predicted saccade latencies in single-saccade visual search. Our observation that there was a shift to earlier discrimination times even when data were aligned on saccade onset might have occurred because of a change in this relationship between DT and RT in multiple fixation trials. To test this hypothesis, we divided the trials for each neuron into short and long RT groups and determined the DT for each group. We did this for both single and multiple fixation trials. We then determined the slope of the relationship between DT and RT. A slope of 1 would indicate that DT is predictive of RT, and that the trial-to-trial variability in RT may be related to differences in visual processing rather than movement programming. Alternatively, a slope of 0 indicates that DT is fixed despite variability in RT, and that trial-to-
trial variability in RT may be more related to differences in movement programming (see Thompson et al., 1996). There were sufficient data in 24 neurons for this analysis. On average, DT/RT slopes in single saccade trials were 0.99 ± 0.13 and not significantly different from 1 (p = 0.93, paired t test), with DT leading RT by 65 ± 4 ms. DT/RT slopes for those same neurons in multiple fixation trials were also not significantly different from 1 (1.0 ± 0.17; p = 0.98) but the lead time was significantly longer than in single fixation trials (92 ± 5 ms; p < 0.0001). DT in multiple fixation trials was therefore equally predictive of RT, though it occurs earlier.

To determine whether an individual neuron’s ability to select a subsequent saccade target is predicted by its discharge properties, we tested for a relationship between both the neuron’s DT and DM in multiple fixation trials and its discharge characteristics. Neither DT nor DM were correlated with a neuron’s position along the visuo-movement index (p = 0.50 and p = 0.32, respectively; Pearson correlation). The same was true when DT and DM were tested against the magnitude of the visually evoked responses (p = 0.88 and p = 0.90) and the peak saccade activity (p = 0.24 and p = 0.20). Moreover, DT and DM were not predicted by a neuron’s discharge rate during the delay period of the delayed saccade task (p = 0.77 and p = 0.52).

We have previously reported that a retention process in this visual search task modulates stimulus representations (Shen and Paré, in preparation): Distracters that have been recently examined have suppressed representations. To determine the degree to which such suppression in distracter activity contributed to the selection process, we eliminated these trials from analysis. These previously examined distracters did not contribute significantly to the early selection process, as results were not different when these distracter trials were removed from analysis (data not shown).

To determine whether the predictive selection of saccade targets can be observed in other visual search tasks as well as in other monkeys, we re-analyzed data from our previous report on the activity of SC sensory-motor neurons in monkeys G and H during a conjunction search task
with an eight-stimulus concentric array (Shen and Paré, 2007). In this previous study, monkeys were allowed an extra 2,000 ms to foveate the target stimulus if their initial saccades landed on a distracter. On ~30% of trials, they needed more than one fixation to acquire the target. For trials in which the animal foveated the target after two fixations, the length of the first fixation in the array was significantly shorter than the time to respond to the array presentation (113 ± 2 vs. 155 ± 1 ms; p < 0.0001, t test). We examined SC neuronal activity on trials in which monkeys made a second corrective saccade to the target that had been brought into the neuron’s RF following the first saccade (as in Murthy et al., 2007). We compared these ‘target’ trials to trials in which a distracter fell in the RF following the first saccade and the monkey made a correct second saccade to the target located outside of the neuron’s new RF position. There were sufficient data (at least five target and five distracter trials) in 16 neurons for this analysis (G: 8; H: 8). Indeed, DT occurred earlier for the selection of this second saccade target (9 ± 9 ms) as compared to the first saccade target in the same subset of neurons (109 ± 4 ms; p < 0.0001, N = 16, t test).

In this previous study, we also showed how the target representation is enhanced even when it is not selected for the first saccade, i.e., SC neuronal activity signals stimulus identity (Shen and Paré, 2007). Given the evidence presented above for the concurrent selection of saccade targets in SC in our concentric array task, could this enhancement in activity actually be related to the stimulus (i.e., target) identity rather than to the selection of the second saccade target? We examined activity during a 25-ms epoch just before saccades in three conditions: target-related activity in two-fixation trials when the subsequent fixation duration was short and when fixation duration was long, as well as distracter-related activity in single fixation trials. We had sufficient data (at least five trials in each condition) in a subset of 20 neurons to perform this analysis. For the example neuron shown in Figure 4.6A, we found an enhancement of target-related activity before a subsequent fixation was made to that target. This enhancement was greater for the shortest fixation durations than for longer ones, consistent with previous findings.
**Figure 4.6 Target identity signals in SC**

**A.** Example SC sensory-motor neuron activity in concentric conjunction search task (see Shen and Paré, 2007). Target-related activity when the monkey makes an initial saccade away from the RF but correctly foveates the target after a second saccade for short (blue) and long (green) intervening fixation durations. Distracter-related activity when the monkey makes a correct saccade to the target away from the RF (dashed black), and target-related activity when the monkey makes a correct saccade to the target in the RF (solid black). Data are aligned to the onset of the first saccade. Gray bar: epoch of analysis (25-ms before saccades).  

**B.** Stimulus identity index (target- / distracter-related activity) for short (blue) and long (green) fixation duration trials. Means of the distributions are indicated.
in a feature search task (2002b). The target-related activity, however, in our conjunction search task in the longest fixation duration trials was still greater than distracter-related activity. To quantify these effects across the sample, we calculated a stimulus identity index by normalizing each neuron’s target-related activity in the two conditions (short and long fixation duration) to its distracter-related activity (Fig. 4.6B). On average, the shortest fixation duration trials had an index greater than that for long duration trials (1.9 ± 0.1 vs 1.6 ± 0.1, p < 0.05, t test), suggesting that the enhancement in activity was related to the concurrent processing of two saccade targets. Both target conditions, however, were still significantly greater than 1 (i.e. distracter-related activity; p < 0.0001, t tests), indicating that the signaling of stimulus identity is independent of the preceding fixation duration in this visual conjunction search task.

4.5 Discussion

We investigated saccade target selection while monkeys executed a multi-fixation search for a target embedded in a structured search array. As in some previous studies, we found that the durations of fixations were significantly shorter than the latency of the initial responses to the search array. Concomitantly, SC sensory-motor neurons displayed discriminating activity significantly earlier when the target was acquired after several fixations, compared to when the target was fixated just after the search array onset. This discriminating activity occurred before the visual afferent delay in over half of the neuronal sample. These data demonstrate that neural representations on the visual salience map are not processed one fixation at a time and how advanced saccade target selection facilitates visual search.

There exists a substantial body of literature that describes the selection of the first saccade goal in response to a search display across a network of structures that form a distributed visual salience map. These previous visual search studies have established how neurons in area LIP (Ipata et al., 2006; Thomas and Paré, 2007), FEF (Thompson et al., 1996; Sato et al., 2001;
Thompson et al., 2005) and SC (Ottes et al., 1987; McPeek and Keller, 2002a; Shen and Paré, 2007) select the saccade goal in advance of saccades. It is consistently reported how these neurons have indiscriminate visual responses to both the target and distracter occur with a latency of 40-60 ms. Thereafter, the target-related activity increases while the distracter-related activity does not, resulting in reliable discriminating activity after ~100-150 ms (Schall et al., 2007). This discrimination time corresponds to ~50-70 ms before saccades. Only a few studies have extended this approach to examine the saccade selection process if there is more than a single saccade, as what happens in active vision.

McPeek and Keller (2002b) showed that, in response to the presentation of the search display, SC neurons have increased activity for a target that will be foveated after a second saccade if the intervening fixation is short. This observation suggests that the target representation remained competitive for selection even after an initial erroneous saccade. Part of this enhancement, however, could also have been due to the representation of target identity separate from the saccade goal (Shen and Paré, 2007). Indeed, we showed here using a (concentric array) conjunction search task how even the target-related activity in two-saccade trials having the longest fixation durations was still enhanced as compared to distracter-related activity. Even more relevant are studies that examine the activity leading up to the selection of the second saccade rather than the first. For example, Murthy and colleagues (2007) trained monkeys to perform a feature search task where the target occasionally jumped to a new location. On trials in which the pop-out stimulus became the second saccade goal, discriminating activity of FEF neurons was found to occur earlier (~40-60 ms following fixation onset) than on single saccade trials. Similarly, a recent study of natural scene search (Phillips and Segraves, 2010) reported FEF neurons with activity predicting the next saccade goal around the time of their visually evoked responses (56 ms following fixation onset). These FEF studies, however, either did not entirely control the placement of the stimulus within the neuron’s receptive field (Murthy et al., 2007) or
did not control for the visual stimulation of the neuron across fixations (Phillips and Segraves, 2010). One approach that affords a more controlled environment with which to study active vision was used by Bichot and colleagues (2005) to examine the activity patterns of V4 neurons during active vision. In this study task, the search stimuli were arranged in a grid pattern such that a stimulus fell in the neuron’s receptive field on nearly all fixations. V4 neurons selected the saccade target ~70-80 ms following stimulus presentation, but the exact timing of the selection when multiple saccades were made as opposed to when a single one was made was not studied.

Related to these search data are anecdotal observations made about LIP neurons during a task in which the visual array remained on throughout a session (Gottlieb et al., 1998). Monkeys were trained to shift their eyes so that one of the stable stimuli fell in the neuron’s receptive field before foveating the cued stimulus. In this task, LIP neurons modulated their activity to signal the location of a relevant stimulus in advance of the saccade that brought the stimulus into the receptive field. The study we present here adds to these previous observations by quantifying the time course of saccade target selection during sequences of fixations and providing evidence for predictive selection in a structure that more closely impacts visual behavior due to its direct outputs to the saccade generating system (Rodgers et al., 2006).

Neuronal activity that is predictive of a stimulus that is about to be brought into the receptive field has been reported in SC (Walker et al., 1995), FEF (Umeno and Goldberg, 1997) and area LIP (Duhamel et al., 1992). In these tasks, a single visual stimulus is displayed, and the monkey is instructed to shift its eyes to a location that will align the receptive field with the stimulus once the saccade is made. This activity has been interpreted to be a possible neural substrate for perceptual stability, where visual receptive fields (and therefore visual stimuli within them) are ‘remapped’ based on an efference copy of the movement program to account for the displacement of those objects once the eyes have moved (Sommer and Wurtz, 2008). Evidence in favor of this account, however, has been difficult to obtain. In fact, reports of ‘change blindness’
wherein significant changes to a visual scene remain undetected across saccades (Henderson and Hollingworth, 1999) and limited memory for visual objects across saccades (Irwin and Andrews, 1996) put into question whether spatial remapping serves to stabilize visual perception. Observations that there is the retention of saccade targets (i.e., locations visited) across saccades (e.g., Beck et al., 2006) and the presence of remapping activity in visual areas within the dorsal but not ventral stream may instead suggest that remapping activity plays a supporting role in action selection (see Bays and Husain, 2007). It is important to distinguish between the predictive visual responses observed in these tasks and the predictive discriminating activity we have reported here. If the early increase in activity were due to remapping of the visual receptive field, the increase in activity should occur for both target and distracter stimuli. We observed, however, that the early modulation in activity is associated only with a stimulus that will become the next saccade target (see Fig. 4.5). Whether there is also a concomitant early increase in response for all stimuli related to the remapping of visual stimuli cannot be determined from our data as there is a stimulus in the neuron’s receptive field on every fixation. In other words, predictive ‘remapping’ activity cannot be distinguished from the activity related to the present receptive field stimulus. It is noteworthy, however, that when tested in less impoverished environments, the occurrence of remapping activity diminishes, even in neurons that show remapping activity in the classic single stimulus paradigm (Churan et al., 2008). The impact of remapping activity in more naturalistic environments has yet to be fully understood.

Previous behavioral observations that fixation durations were shorter than initial response times during visual search tasks were interpreted with the view that the processing of at least two saccades can occur in parallel (Viviani and Swensson, 1982; Hooge and Erkelens, 1996; Theeuwes et al., 1998; McPeek et al., 2000; McPeek and Keller, 2001; see also Sommer, 1997; Findlay et al., 2001; Godijn and Theeuwes, 2002). Our current findings add to this literature by showing how the selection of a subsequent saccade target can occur before it is brought into the
neuron’s receptive field. The relationship, however, between the selection of a saccade goal and the programming of the movement itself has been shown to be dissociated in FEF (Thompson et al., 1996) as well as for some neurons in SC (McPeek and Keller, 2002a). The DT/RT slopes of these neurons therefore tend towards 0, such that saccade latencies cannot be predicted by DTs. In the present study, saccade latencies were predicted by DTs for both single and multiple saccade trials, as DT/RT slopes were distributed around 1. The time difference between neuronal discrimination and saccade initiation in these two types of fixations suggests, however, that the process of saccade target selection is distinct from saccade programming. This is consistent with the view that a selection threshold exists separate from the saccade trigger threshold (Shen and Paré, 2007). The observation that the selection of the subsequent saccade target occurred nearly 90 ms in advance of saccade initiation suggests that there is ample time for that saccade to be countermanded. In other words, there is not necessarily a commitment of a saccade program to the selected item.
4.6 References


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Chapter 5
General Discussion
In the three preceding chapters, I have shown how the superior colliculus is an important node in the neuro-cognitive network that instantiates the visual salience map. The salience map is believed to be important for the guidance of overt (visual behavior) and covert visual attention and is proposed to contain representations of objects whose magnitudes dictate the probability of selecting them for the next saccade goal. These multiple representations are shaped by both stimulus-driven inputs from feature maps and goal-directed signals. The map is organized topographically, not selective for features, and the competition between the multiple representations is believed to be resolved via winner-take-all mechanisms.

In Chapter 2, I reported how SC activity is modulated by feature-based context and predicts the flexible visual behavior associated with contextual changes. This was achieved using a variable distracter-ratio paradigm, whereby the context within which a conjunction search target is situated is manipulated by varying the ratio between different distracter types. The feature-based modulation that I observed was independent of the saccade goal, suggesting that it was not due to the planning of eye movements. Rather, it was a representation of the salience of visual objects in the display. Moreover, I showed how this modulation was in part due to a goal-directed signal in addition to the stimulus-driven inputs: There was also neuronal modulation related to the feature of the previous session’s target even in balanced displays. Moreover, the feature-based modulation arose around the time of saccade target selection and its timing was comparable to previous accounts of modulation of cortical neurons by feature-based attention. This first study unequivocally demonstrated that SC is within the distributed network that forms the visual salience map by showing that it both predicts behavior in different contexts and is influenced by goal-directed signals.

In Chapter 3, I reported a neural correlate for the retention of visual objects during active vision, in which the suppression of representations at locations already examined may prevent their re-fixation and guides visual attention to not yet examined locations. The suppression is
maintained for up to three intervening fixations, suggesting that it is not due to a transient mechanism such as inhibition-of-saccade-return. The additional observation that the suppression is sustained throughout the fixation duration parallels the observations of persistent activity throughout the neurocognitive network during working memory tasks (Bruce and Goldberg, 1985; Gnadt and Andersen, 1988; Funahashi et al., 1989; Glimcher and Sparks, 1992; Munoz and Wurtz, 1995; Paré and Wurtz, 2001; Sommer and Wurtz, 2001). Taken together, these findings suggest a neural mechanism by which representations on the working memory map actively suppress the representations of examined locations at the level of the salience map.

In Chapter 4, I showed how the selection of a saccade target during active vision was predictive, occurring earlier than for the first saccade target and often before the arrival of new visual information during the fixation that preceded target acquisition. This early selection was accompanied by the shortening of fixation durations and was predictive of the onset of saccades following those fixations. The relationship between the selection and movement onset, however, was not fully preserved as the time between the two events lengthened for subsequent fixations. These findings suggest that the selection of saccade targets from multiple representations on the salience map during active vision does not occur one fixation at a time. Instead, the early selection of subsequent saccade targets facilitates visual search behavior.

The distinction between saccade target selection and saccade programming provides the first of several implications about the neural mechanisms underlying active vision. This finding is supported by previous descriptions of a selection threshold in SC separate from the saccade trigger threshold before single saccades (Shen and Paré, 2007). Additional evidence is provided by studies in FEF, where neurons have been shown to select visual singletons even if the saccade response is in the opposite direction (Sato and Schall, 2003) or if the response does not involve an eye movement (Thompson et al., 2005). Second, the visuo-motor function of neurons during active vision may not be related to their discharge characteristics determined from memory- or
visually-guided delayed saccade tasks. SC neurons have previously been classified as ‘prelude
bursters’ or ‘buildup’ neurons (those having significant delay period activity) and ‘burst’ neurons
(those without significant delay period activity) (Glimcher and Sparks, 1992; Munoz and Wurtz,
1995). Some studies of saccade target selection have reported the presence of selective activity
only in ‘buildup’ or ‘prelude burst’ neurons (Glimcher and Sparks, 1992; Basso and Wurtz, 1998;
Horwitz and Newsome, 1999; Krauzlis and Dill, 2002), and even separate roles of visual and
movement selection for distinct subsets of prelude neurons (Horwitz and Newsome, 2001a) or
neurons with and without visual responses (Ignashchenkova et al., 2004), while ‘burst’ neurons
are not believed to be involved in the process of saccade target selection. Interpreting the role of
SC from these previous studies is, however, limited given their task designs and the distinctions
made between neuronal classes. First, the use of only a few (usually two) stimuli (Goldberg and
Wurtz, 1972; Wurtz and Mohler, 1976; Ottes et al., 1987; Krauzlis and Dill, 2002; Port and
Wurtz, 2009) does not necessarily invoke a true competition between multiple stimuli that exists
during a selection process. Rather, a cue that instructs the monkey as to which stimulus is to be
looked at renders such studies unable to distinguish between the process of selecting the visual
target for a saccade and the programming of the saccade itself. Moreover, tasks in which there is
an imposed delay (Glimcher and Sparks, 1992; Basso and Wurtz, 1998; Horwitz and Newsome,
1999, 2001a, b; Ignashchenkova et al., 2004) may elicit early selection so that the process of
selection may have already occurred well before the saccade is made. Finally, arbitrary imposed
delays may even elicit responses that are not present in more naturalistic environments. Indeed, in
visual search tasks where these delays are not present, no differences in discrimination ability
have been reported between SC neuronal classes (McPeek and Keller, 2002; Shen and Paré,
2007). I have extended these findings to show how discharge characteristics also do not predict
visuo-motor function in active vision, suggesting that the processes of saccade target selection
and saccade target retention are provided by groups of neuron working as ensembles (see Shen
and Paré, 2007). The variety of neuronal responses observed in delayed saccade tasks may be due to variability in their cellular make-up (e.g., differences in membrane impedance) and/or differences in inputs. These differences, however, do not seem to affect the functional role of SC neurons in active vision.

The neurophysiological findings reported here can also inform models of selective attention and visual search (e.g., Cave and Wolfe, 1990; Findlay and Walker, 1999; Itti and Koch, 2000; Hamker, 2006), which should be constrained in two ways. First, there may be no separate motor map from the visual salience map as the intermediate layers of SC seem to serve both functions. SC should instead be considered as a visual salience map for eye movements, in which the outcome of a competition between multiple representations within SC provides a single motor output via its direct connections to the brainstem saccade generating circuit once the saccade trigger threshold is reached. Second, the process by which previously examined objects are retained during active vision is not infinitely long, nor are those representations on the visual salience map completely abolished. Models should instead incorporate a limited capacity retention process that only temporarily prevents the selection of previously examined representations but does not eliminate them from future selection. This partial suppression of representations on the salience map is also observed in different contexts (Glimcher and Sparks, 1992; Dorris and Munoz, 1998; Dorris and Glimcher, 2004; Ipata et al., 2006; Mirpour et al., 2009), suggesting that a similar mechanism might exist to decrease, but not entirely abolish, the probability of that representation being selected.

Owing to its centralized position within the neuro-cognitive network, SC is a valuable brain structure for the study of cognitive processes in primates as signals from other nodes in the network essentially culminate in the SC before behavior is generated. The SC is a phylogenetically old brain structure that is crucial to the control of orienting behaviors and it is highly conserved across all vertebrate radiations (Butler and Hodos, 2005). The parallel between
the flexible modulation of SC activity due to featural context that I observed and the evidence of flexible orienting behavior in different (prey vs. predator) contexts in the frog (Ewert et al., 2001) suggests that some functional features of SC may have been preserved across species. What has changed in the primate SC, however, are its inputs from cortical areas, specifically prefrontal and posterior parietal cortices. These inputs are considered evolutionarily recent – limited mainly to anthropoid primates (Preuss, 2007). In light of these evolutionary considerations and the observation that the organization of neural circuits tends to be highly conserved across species (Katz and Harris-Warrick, 1999), it is unlikely that the cognitive functions of the SC were entirely replaced by frontal and parietal areas but rather elaborated with cortical areas to enhance behavioral flexibility.

I see two alternative interpretations of SC evolution. The first is that SC functions have been conserved over time, and one might expect to find similar observations of cognitive function in other vertebrates. In contrast, the same underlying tectal circuitry may have been co-opted for slightly different functions via the modulation from cortical inputs. This interpretation may be supported by observations in simpler nervous systems. For example, two different species of electric fish have the same neural circuitry for controlling avoidance behavior, but the premotor inputs that modulate this circuit differ between the two species. In one species, the *Eigenmannia*, avoidance behavior can involve both the raising and lowering of the discharge frequency of its electric organ, while the *Apteronotus* species can only raise its baseline discharge frequency (Heiligenberg et al., 1996). Differences in inputs, then, result in different behavioral responses despite similar neural circuitry. Similar observations of species-specific behavior owing to modulation of analogous circuits by different extrinsic inputs have been reported in tadpoles and crustaceans (see Katz and Harris-Warrick, 1999). A parallel in the primate neuro-cognitive network can be drawn using recent evidence that PPC neurons may only serve to modulate rather than control saccade production (Brunamonti et al., 2008) – in contrast to SC’s role in controlling
saccades (Paré and Hanes, 2003). Whether these modulatory inputs have fully altered collicular function in the primate as compared to other vertebrates will require a thorough cross-species understanding of tectal function through comparative neurobiology.
5.1 References


Chapter 6

Summary and Conclusions
In this thesis, I have described the role of the primate superior colliculus in visual behavior. I combined the use of the visual search paradigm with single-neuron recording techniques to advance our understanding of this brain structure’s role within the network responsible for cognitive processes such as selective visual attention and visual working memory.

In Chapter 2, I demonstrated how SC is part of the visual salience map. Using a variable distracter-ratio search task, I reported how monkeys’ visual behavior was adaptive to the featural context provided by the display, and how SC sensory-motor activity was predictive of this behavior. I also showed how, in addition to stimulus-driven signals, SC neurons are influenced by goal-directed signals: they show feature-based modulation based on monkeys’ past experiences with those features. Together with previous findings that such sensory-motor neurons output directly to the circuitry responsible for the generation of saccades, Chapter 2 highlighted how the SC’s position within the neuro-cognitive network affords it a unique role in bridging perception and action.

In Chapter 3, I described how representations on the visual salience map are updated from fixation to fixation. Using a large visual search display, I reported how monkeys had a limited capacity for the retention of previously inspected items and this capacity was comparable to what was previously reported in humans. I investigated the neural basis of this retention process and found suppressed SC sensory-motor activity related to stimuli that were presumably retained.

In Chapter 4, I described how multiple representations on the salience map are dynamically processed. I showed how short fixation durations were accompanied by the early selection of saccade targets in a sequence of fixations, and how the process of selecting a saccade target may become temporally dissociated from the programming of the eye movement in active vision. Together, Chapters 3 and 4 serve to advance our current understanding of the neural mechanisms underlying active vision.