

Chapter 1

The Relationship Between Exogenous and Endogenous Saccades and Attention

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Visual scenes typically contain many objects that compete for the control of attention and saccades, on the basis of their intrinsic salience (exogenous control) or their relevance for the goals of the observer (endogenous control). The present chapter reviews the evidence regarding the relationship between endogenous and exogenous attention and saccades. Furthermore, a competitive integration model is presented, which provides a framework for understanding exogenous and endogenous control of saccades as well as the relationship between attention and saccades.

Introduction

During our everyday lives we are continuously confronted with a visual environment containing a vast amount of information. In order to interact adaptively with the environment we need to select the information that is relevant for our goals and to ignore what is irrelevant. Selection may be achieved by overt orienting (saccades), which allows the high acuity fovea to be directed to the focus of interest, or by covert orienting (attention), which facilitates the processing of selected objects without shifting the gaze direction. A fundamental research question concerns the mechanisms that control what parts of the visual scene are selected. On the one hand, selection may be controlled by stimulus properties, irrespective of the goals of the observer. For example, a salient new object suddenly appearing in the visual field will capture our attention (e.g. Yantis & Jonides, 1984; Jonides & Yantis, 1988; Theeuwes, 1994, 1995) and our eyes (e.g. Theeuwes *et al.*, 1998, 1999) even if it is irrelevant for the task at hand. This control mode is known as exogenous control (or stimulus-driven, involuntary, bottom-up). On the other hand, selection may be controlled by our goals and expectations. For example, when we are searching for a specific target object we will

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tend to select objects that share one or more feature with the target (e.g. Treisman & Gelade, 1980; Wolfe *et al.*, 1989; Findlay, 1997). This control mode is known as endogenous control (or goal-directed, voluntary, top-down).

Over the past 20 years a great deal of research has been conducted to determine the relationship between (endogenous and exogenous) shifts of attention and saccades. Since attention and saccades both have the goal of selecting the relevant portions of a visual scene, the idea that attention and saccades are to a certain extent related is intuitively appealing. In this view attention and saccades are related on the basis of their common function. That is, in order to further process and respond to an object, both orienting systems are typically directed to the same object, although in principle their focus may be dissociated. An alternative view which assumes a tighter relationship between attention and saccades is the efference view (Posner, 1980). According to this view attention is required at the saccade destination in order to program a saccade. Furthermore, attention shifts are accomplished by preparing an eye movement to that location (e.g. Klein, 1980; Rizzolatti *et al.*, 1987). This does not imply that whenever attention moves the eyes must follow. It is assumed that attention and saccade programming are causally related, but a separate go-signal is required to trigger the saccade that has been programmed (e.g. Deubel & Schneider, 1996; Rizzolatti *et al.*, 1987). Therefore, attention may move while the eyes remain fixated (e.g. Posner, 1980).

The central goal of this chapter is to provide an overview of the evidence regarding the nature of the relationship between attention and saccades for exogenous and endogenous orienting. Furthermore, a competitive integration model will be presented (Godijn & Theeuwes, in press-a; in press-b) in which exogenous and endogenous saccades are programmed within a common saccade map. This model provides a framework within which the relation between attention and saccades may be understood.

Although there have been quite a few studies examining the relationship between attention and saccades during reading (e.g. Morrison, 1984; Henderson & Ferreira, 1990; Henderson, 1992; Reichle *et al.*, 1998) we consider this a separate issue with quite specific demands on the attentional and oculomotor systems. Therefore these studies will not be discussed.

Attention and Endogenous Saccades

The most common method to examine the relationship between attention and saccades has been the dual-task paradigm (e.g. Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, *et al.*, 1995; Shepherd *et al.*, 1986). Typically, the primary task is an eye movement task in which the participant is required to execute a saccade to a peripheral movement task in which the participant is required to execute a saccade to a peripheral saccade goal, which is indicated by a symbolic cue (e.g. an arrow presented in the centre of the visual field). The secondary task is usually a manual response task toward a probe stimulus which is either presented at the saccade target location or somewhere else in the visual field. The rationale behind this procedure is that, if attention precedes the eyes, identification and detection of a probe

stimulus should be facilitated when it is presented at the saccade destination compared to when it is presented at a different location. There is quite some evidence that when an endogenous saccade is executed towards a particular location, performance on the secondary manual response task is better when the probe stimulus is presented at the saccade target location than when it is presented somewhere else in the visual field. For example, Kowler *et al.* (1995) conducted a series of experiments in which participants were required to make a saccade while performing a letter identification task. Participants viewed displays containing eight pre-masks on a circular array surrounding a central fixation cross. A saccade was executed to one of the peripheral objects as indicated by a central arrow. Simultaneously with the onset of the arrow, the pre-masks were replaced by letters, which were masked 200 ms later. In the random report condition the letter "Q" appeared randomly at one of the display locations at the end of the trial and participants were instructed to report the letter that had appeared there. In the fixed report condition participants were always required to report the letter at a fixed location. The results showed that in the random report condition identification accuracy was best when the saccade goal and letter target were at the same location, which indicated that attention had preceded the eyes to the saccade goal. However, in the fixed report condition identification accuracy was always very good and did not depend on the location of the saccade goal. Kowler *et al.* suggested that in the fixed report condition participants might have focused on the letter identification task before programming the saccade. Indeed, saccade latencies were 50–75 ms higher in the fixed report condition than in the random report condition. In a subsequent experiment Kowler *et al.* examined the possible interference between the letter identification task and the eye movement task by requiring participants to perform the tasks either alone or together under varying priority instructions. The results revealed a trade-off between the two tasks, but in this experiment an advantage for letters presented at the saccade destination was found in the fixed report condition as well as in the random report condition.

Other dual-task studies that have used discrimination tasks to assess attention allocation have also found perceptual benefits at the saccade destination (e.g. Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995). Furthermore, the results of these studies indicate that the coupling between selective attention and saccades is obligatory, since the perceptual benefits were still found when participants had preknowledge of the discrimination target location.

Even though the studies discussed above indicate a strong relationship between attention and endogenous saccades, it appears that this relationship only exists when an identification task or a discrimination task is used as a secondary task. If the secondary task is a detection task the results are less clear-cut. For example, Remington (1980) used a threshold detection task in which on half of the trials a brief luminance increment occurred at one of three positions (left, center, right). The luminance increment occurred at varying stimulus-onset-asynchronies (SOAs) relative to the presentation of a central arrow cue, which indicated the saccade goal. The results revealed no effect of saccade goal on detection accuracy when the luminance increment occurred during the interval between presentation of the saccade cue and saccade execution. Remington interpreted these results as evidence that attention did not precede endogenous

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saccades (see also Klein, 1980). There appears to be only one study that did find perpetual benefits at the saccade destination using a detection task (Shepherd *et al.*, 1986). However, as pointed out by Hoffman (1998) the results of Shepherd *et al.* are hard to interpret, since in their study the detection probe remained visible until after the manual response. Since the manual response often occurred after the eyes had moved, the perceptual benefits at the saccade destination could have been due to the facilitated processing of foveated probes.

Another task that requires the detection of stimuli is the temporal order judgment task (TOJ task; e.g. Stelmach & Herdman, 1991; Maylor, 1985). In a TOJ task two stimuli are presented in the periphery and participants are required to judge which stimulus was presented first. This task has been found to be sensitive to attentional allocation (e.g. Stelmach & Herdman, 1991; Maylor, 1985). That is, if one of the TOJ stimuli is presented at the attended location, this stimulus is judged to have appeared first on the majority of trials on which both TOJ stimuli are presented simultaneously. Stelmach *et al.* (1997) used this task to examine the relationship between attention and endogenous saccades. Participants executed a saccade in the direction indicated by an auditory cue ("left" or "right") or they maintained fixation when the auditory cue "center" was presented. After a varying SOA relative to the saccade cue the TOJ stimuli were presented. The rationale was that if attention preceded the eyes the stimulus at the saccade destination should have been judged to have appeared first on the majority of trials. The results revealed no effect of saccade destination, suggesting that attention did not precede the eyes.

When examining these results it is not immediately clear why the relationship between attention and endogenous saccades cannot be established when a probe detection task or a TOJ task is used. One possible explanation is provided by Stelmach *et al.* (1997). They argued that there may be two types of attention referred to as selective and preparatory attention. According to their view, identification tasks assess selective attention while detection tasks assess preparatory attention (Stelmach *et al.*, 1997; also see LaBerge, 1995). When a number of objects are present in a visual scene selective attention allows processing operations to be performed on the selected object while the other objects are ignored (or "filtered out"). Preparatory attention refers to an attentional shift to a specific location in anticipation of a specific object. That is, preparatory attention operates on the basis of expectations concerning when and where a task-relevant object will appear. Stelmach *et al.* argued that selective attention may operate in the order of hundreds of milliseconds. This would explain why tasks that have assessed selective attention (e.g. identification and discrimination tasks) have provided evidence for a strong link between attention and saccade programming while tasks that have assessed preparatory attention (e.g. detection and TOJ tasks) have not. Since endogenous saccade latencies range from 200–400 ms, preparatory attention may be too slow to precede a saccade. Furthermore, since attention and saccades have the common function of selecting the relevant information in a visual scene, it makes intuitive sense that selective attention precedes saccades, but preparatory attention does not. In fact, according to Schneider and Deubel (Schneider & Deubel, 2002; Schneider, 1995; Deubel & Schneider, 1996) attention is a common selection mechanism for saccades (or actions in general) as well as for perception.

Another speculation might be that a detection task does not need the same focused attention as identification tasks do. There is evidence that the detection of simple features (i.e., a probe onset) can proceed pre-attentively without the need for focused attention. Indeed, participants may “know” that something was presented but may not know where in the visual field this occurred (Sagi & Julesz, 1985). The detection of a basic feature may occur without the necessity of allocating spatial attention and the generation of a spatial code for the execution of the endogenous saccade and the (pre-attentive) detection of the probe may therefore proceed without any interference. In other words, detection of probes may not benefit from the allocation of spatial attention and therefore it may appear that there is no relation between attention and endogenous saccades when a detection task is used.

Attention and Exogenous Saccades

The evidence reviewed in the previous section suggests that attention does precede endogenous saccades. An equally fundamental question is whether attention also precedes exogenous saccades. Exogenous saccades are saccades that are triggered by some event in the environment and are executed independent of the goal of the observer. It is well known that abrupt onsets have the ability to capture attention independent of the goals of the observer (Yantis & Jonides, 1984; Theeuwes, 1991, 1994, 1995). Therefore, it is likely that abrupt onsets may also elicit exogenous saccades. Thus, similar to the paradigms employed to investigate endogenous saccades, in a number of dual-task studies abrupt onsets were presented in the periphery to elicit “exogenous” saccades and performance on a secondary manual response task, sensitive to attentional allocation, was examined. With this type of set-up, several studies have indeed found a consistent relationship between attention and exogenous saccades (e.g. Remington, 1980; Posner, 1980; Stelmach *et al.*, 1997; Schneider & Deubel, 2002). However, there is a fundamental methodological issue to consider. The question is whether in these studies the saccades made toward the onset were truly “exogenous”. Participants received the instruction to make an eye movement toward the abrupt onset and this added an endogenous component to the exogenous properties of the abrupt onset. The only way to investigate genuine exogenous saccades is to provide an explicit endogenous saccade goal that is different from the location of the abrupt onset. If a saccade is made to the onset even though the observer had the intention to execute a saccade toward another goal only then one can speak of an exogenous saccade.

In the literature there appear to be only two paradigms that fulfil these requirements and are able to generate genuine exogenous saccades. First, in the anti-saccade task (e.g. Hallet, 1978; Mokler & Fischer, 1999) an abrupt onset is presented in the periphery and participants have the task of executing a saccade in the opposite direction. Saccades that are correctly executed toward the opposite location (so-called anti-saccades) are considered to be endogenous while saccades that are erroneously executed toward the onset (pro-saccades) are considered exogenous (e.g. Klein & Shore, 2000). Typically participants make these erroneous pro-saccades on about 10

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to 30% of the trials, depending on the specific characteristics of the task (e.g. Fischer & Weber, 1992, 1996; Mokler & Fischer, 1999). For example, when the fixation point is removed shortly before the onset appears the proportion of erroneous pro-saccades is increased (e.g. Fischer & Weber, 1992; Reuter-Lorenz *et al.*, 1995). Latencies of exogenous pro-saccades are generally significantly shorter than latencies of endogenous anti-saccades (e.g. Hallet, 1978).

A second paradigm that is assumed to generate genuine exogenous saccades is the oculomotor capture paradigm (e.g. Theeuwes *et al.*, 1998, 1999). In this task, participants viewed displays containing six equi-spaced grey circles presented on an imaginary circle around a central fixation point. After one second all of the circles but one changed to red. Participants had the explicit instruction to make a saccade towards the only grey element in the display. On some trials, an irrelevant red circle, presented with an abrupt onset, was added to the display. In Theeuwes *et al.* (1999) a control condition was used in which an additional non-onset distractor was added to the display at the beginning of the trial. In Theeuwes *et al.* (1998) there was no additional non-onset distractor on trials without an onset. The results of both studies showed that when no onset was added to the display, observers generated endogenous saccades that went directly towards the uniquely coloured circle. However, on those trials on which an onset was added to the display, the eyes went in the direction of the onset on about 30 to 40% of these trials, stopped briefly, and then went on to the target. Figure 1.1 shows the results. The graphs on the left side depict the control condition without the onset; the graphs on the right side depict the condition in which an onset was presented. Note that in the condition with the onset, the eyes often went to the onset. This occurred even when the onset appeared on the opposite side of the target circle, although the proportion of saccades to the onset was greater at a 90° separation than at a 150° separation.

Since participants were required to execute a saccade to the uniquely coloured elements they had a clear top-down goal. However, despite this endogenous goal, on about 30 to 40% of the trials on which an onset was presented a saccade was executed toward the abrupt onset (see Figure 1.1). These saccades can be considered as genuinely exogenous, since they are completely irrelevant for the task at hand and were executed even though there was an explicit instruction to move the eyes to another location. Saccades made to the colour singleton are considered endogenous (e.g. Theeuwes *et al.*, 1998, 1999; Klein & Shore, 2000).

The oculomotor capture paradigm has a few advantages over the anti-saccade task (see also Klein & Shore, 2000). First, the location of the target is completely independent from that of the onset. In contrast, in the anti-saccade task the anti-saccade location is defined in terms of the location of the onset (i.e. the anti-saccade location is always opposite the onset). Second, in the oculomotor capture paradigm the competition between exogenous and endogenous saccades can be examined by comparing saccade behaviour on trials on which an onset is presented with trials on which no onset is presented. This is obviously impossible in the anti-saccade task. Third, in the anti-saccade task there are often not enough erroneous pro-saccades to allow a reliable statistical analysis. Several additional manipulations have been used to increase the number of pro-saccades. For example, by removing the fixation point and by

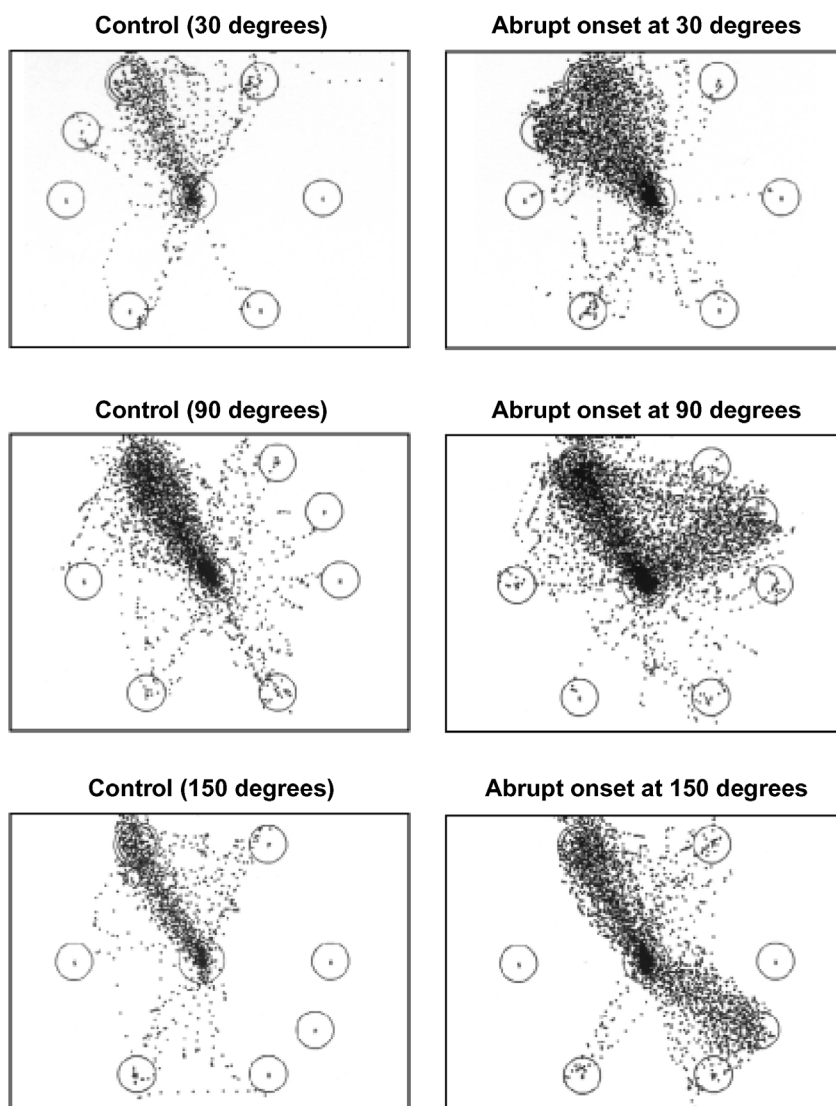


Figure 1.1: Oculomotor capture. Data from Theeuwes *et al.* (1999). Eye movement behaviour in the condition in which an abrupt onset was presented simultaneously with the target. The results are collapsed over all eight participants and normalised with respect to the position of target and onset. Sample points (every 4 ms) were only taken from the first saccade. Left panels: Eye movement behaviour in the control condition in which no abrupt onset was presented. Right panels: Eye movement behaviour in the condition in which an abrupt onset was presented; Either close to the target (TOP), somewhat away from the target (MIDDLE) or at the opposite side from the target (BOTTOM). From Theeuwes *et al.* (1999).

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presenting a pre-cue at the saccade location before the imperative stimulus (e.g. Mokler & Fischer, 1999) researchers were able to increase the percentage of pro-saccades to about 20%. However, additional manipulations such as the presentation of a pre-cue may affect the allocation of attention when an exogenous pro-saccade or endogenous anti-saccade is programmed. Note that in the oculomotor capture paradigm exogenous saccades to the onset are elicited on about 30% of the trials even without additional manipulations such as pre-cues and offset of the central fixation point.

Now that we have introduced two paradigms in which genuine exogenous saccades are generated we can address the question whether there is a relationship between attention and exogenous saccades. To date there are not many studies that have addressed this issue.

Attention and Exogenous Saccades in the Anti-saccade Paradigm

Recently, two (unpublished) studies have examined the attentional allocation prior to exogenous and endogenous saccades in the anti-saccade task. Both studies used a dual-task paradigm in which the primary task was an anti-saccade task and the secondary task was a letter discrimination task. In Mokler *et al.* (2000) participants viewed displays containing two figure-eight pre-masks left and right of a central fixation point. After one second there was an onset of the anti-saccade stimulus around one of the pre-masks. In order to raise the probability that participants would generate erroneous pro-saccades to the onset of the anti-saccade stimulus the fixation point was removed 200 ms before the onset of the anti-saccade stimulus (e.g. Fischer & Weber, 1992) and a 100% valid pre-cue was presented at the location to which a saccade would be required (e.g. Fischer & Weber, 1996; Mokler & Fischer, 1999). Some line segments of the pre-masks were removed 20 or 120 ms after the onset of the anti-saccade stimulus, revealing two letters. One of the letters was the discrimination target ("E" or "reversed E"). Another 100 ms later the letters were masked. Participants were required to execute a saccade in the opposite direction of the anti-saccade stimulus and to determine the identity of the discrimination target. Furthermore, in addition to the typical secondary manual response task, participants were required to indicate whether they thought they had made an erroneous pro-saccade to the onset of the anti-saccade stimulus. The results showed that erroneous pro-saccades were made on 20% of the trials. On 57% of these trials participants were unaware that they had made a pro-saccade. When the eyes went directly to the saccade target location discrimination accuracy was highest when the discrimination target was presented at the saccade target location, suggesting that attention preceded endogenous anti-saccades. When erroneous pro-saccades were perceived discrimination accuracy was highest when the discrimination target was presented at the location of the anti-saccade stimulus. However, when erroneous pro-saccades were unperceived discrimination accuracy was highest when the discrimination target was presented at the saccade target location. According to Mokler *et al.* (2000) this suggested that unintended saccades could be executed without a presaccadic shift of attention. However, this lacked an adequate control condition. Since there was no non-attended control location it could not be

determined whether attention moved to both locations or to just one (see Godijn & Theeuwes, in prep. showing evidence for the parallel allocation of attention to two non-contiguous locations when preparing two saccades).

Another recent study by Irwin *et al.* (submitted) was very similar to Mokler *et al.* In Irwin *et al.* a pre-cue was also used to induce erroneous pro-saccades. However, the pre-cue was completely non-predictive of the saccade target location, whereas in Mokler *et al.* (2000) the precue was 100% valid. Another difference compared to Mokler *et al.* (2000) was that the discrimination letters were briefly flashed in Irwin *et al.* but not masked as in Mokler *et al.* In contrast to the results of Mokler *et al.* (2000) discrimination accuracy was always higher at the location to which the eyes moved compared to the opposite location. Furthermore, discrimination accuracy did not differ between trials on which the erroneous pro-saccades were perceived and those on which they were not. These results suggest that attention preceded endogenous saccades to the saccade target location as well as exogenous saccades to the anti-saccade stimulus.

One factor that may have affected the results in both Mokler *et al.* and Irwin *et al.* is the presentation of the pre-cue. In Mokler *et al.* it always indicated the saccade target location, but in Irwin *et al.* it was non-predictive of the saccade target location. Previous research has shown that when peripheral cues are non-predictive of the target location, responses to a target presented at least a few hundred milliseconds later at the cued location are delayed (e.g. Posner & Cohen, 1984; Rafal *et al.*, 1989) and discrimination performance at that location is impaired (Lupiañez *et al.*, 1997; Pratt *et al.*, 1997). This phenomenon, known as inhibition-of-return (Posner & Cohen, 1984) will be discussed further in the following section. Since the vast majority of erroneous pro-saccades in Irwin *et al.* were made when the anti-saccade stimulus appeared at the location opposite the pre-cue it is possible that discrimination accuracy was higher at the location of the anti-saccade stimulus than at the saccade target location, because of inhibition-of-return (IOR) to the location of the precue.

Taken together, on the basis of the studies by Mokler *et al.* (2000) and Irwin *et al.* (submitted) it is unclear whether attention precedes exogenous saccades in the anti-saccade paradigm.

Attention and Exogenous Saccades in the Oculomotor Capture Paradigm

Theeuwes *et al.* (1999, Experiment 2) addressed the question whether exogenous saccades to the onset in the oculomotor capture paradigm are preceded by a shift of attention. Participants had to make a saccade to the uniquely coloured grey circle in order to identify a small letter (C or reversed C) contained within it. In addition, a large irrelevant letter was presented at the location of the onset. This letter could be either congruent or incongruent with the letter inside the uniquely coloured grey circle. Due to the relatively large size of the letter inside the onset its identity could be determined by a shift of covert attention. In other words, it was not necessary to execute a saccade to the location of the onset to identify the letter inside it. On congruent trials,

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the large letter was identical to the letter appearing in the singleton target, so that the letter inside the onset activated the same response as the letter in the singleton target. On incongruent trials, the large letter was different from the letter appearing in the singleton target, so that the large letter activated the inappropriate response. Theeuwes *et al.* reasoned that if congruency of the letter inside the onset would have an effect on responding to the letter contained in the grey target circle, attention must have shifted to the location of the onset. The results indicated a reliable congruency effect on trials on which the eyes went directly to the target. Theeuwes *et al.* concluded that regardless of whether an exogenous saccade was executed toward the onset, attention always went to the location of the onset.

However, the method employed by Theeuwes *et al.* (1999) was problematic for a number of reasons. First, because a large response-relevant letter was present at the location of the onset, this location may have received attention, not because an irrelevant element was presented at that location, but because an element was presented that contained a large and response-relevant letter. If the response-relevant identity of the letter in the onset attracted attention to that location, it is hard to claim that it was the onset that captured attention. A second reason for questioning the congruency manipulation of Theeuwes *et al.* (1999) was offered by Folk and Remington (1998). In line with the notion of perceptual load (Lavie, 1995), they suggested that when the number of objects is small, identity information can influence response mechanisms in parallel. In other words, they claimed that attention may have gone in parallel to both the singleton target and the onset containing the large letter causing a congruency effect on responding.

A recent study by Godijn and Theeuwes (in press-a) examined whether inhibition-of-return (IOR) occurs at the location of the onset in the oculomotor capture paradigm. Although this study is relevant for this issue, since the standard claim underlying inhibition-of-return (IOR) is that attention is inhibited from returning to a previously attended location (e.g. Posner & Cohen, 1984; Pratt *et al.*, 1997). Furthermore, saccades are also inhibited from moving to a previously attended location (e.g. Abrams & Dobkin, 1994). Similar to Theeuwes *et al.* (1999) participants were instructed to execute an endogenous saccade to a uniquely coloured target while a task-irrelevant onset was presented at a different location. After fixating the initial target another object became the next saccade target. This was done by changing the colour of one of the distractor circles into the target colour (from red to gray). The new target was presented at the location at which the onset had previously appeared or at the location of one of the non-onset distractors. The results confirmed earlier findings of Theeuwes *et al.* (1999) that attention was captured by the onset even when the eyes went directly to the target; Saccade latencies to the second target were longer when the new target appeared at the location at which the onset had appeared than when it appeared at another location. The size of this IOR effect was the same regardless of whether the eyes first went to the onset or to the initial target location.

The evidence from Godijn and Theeuwes (in press-a) that onsets capture attention even when the eyes go directly to the target is indirect and based on the assumption that IOR reflects the previous allocation of attention. No study has directly examined the allocation of attention in the oculomotor capture paradigm. Therefore, further

research is needed to address this issue. Using a dual-task paradigm with the oculomotor capture paradigm instead of the anti-saccade task would have a number of distinct advantages. First, discrimination targets may also be presented at non-onset distractors at which attention is typically not directed (e.g. Theeuwes *et al.*, 1998, 1999). This would provide a suitable control condition with which discrimination accuracy of targets at the saccade target and onset may be compared. Second, in the oculomotor capture paradigm a condition in which an onset is presented may be compared with a condition in which no onset is presented. If attention is captured by the onset on trials on which the eyes directly move to the saccade target it may be expected that discrimination accuracy of letters presented at the saccade target location is higher when the eyes go to the saccade target on no-onset trials than on onset trials.

Exogenous Saccades and Awareness

The question whether attention precedes exogenous saccades has also been addressed by examining observers' conscious awareness (e.g. Mokler & Fischer, 1999). In fact, Mack and Rock (1998) have argued that conscious awareness is a prerequisite of attention. Thus, if a specific object did not reach conscious awareness it could not have captured attention. Likewise, it has been suggested that the awareness of gaze position depends on attentional allocation (e.g. Deubel *et al.*, 1999; Mokler & Fischer, 1999). This idea is supported by a study by Deubel *et al.*, (1999). In this study participants had the task of executing a saccade to a target location. Furthermore, a probe stimulus was presented at varying SOAs relative to the signal to move the eyes. At the end of the trials participants were required to indicate where they were looking when the probe stimulus appeared. The results showed that they tended to judge that they were looking at the saccade location well before they actually moved their eyes. Since it is assumed that attention precedes the eyes to the saccade destination, Deubel *et al.* concluded that the attended location was typically misinterpreted as the gaze position.

If it is assumed that the perception of gaze position requires attention then it is possible that saccades that go unnoticed by observers are not preceded by attention. A number of studies have in fact shown that observers are often unaware that they execute exogenous saccades toward onsets in the anti-saccade task (e.g. Mokler & Fischer, 1999; Mokler *et al.*, 2000) and in the oculomotor capture paradigm (Theeuwes *et al.*, 1998, 1999). Mokler and Fischer (1999) interpreted this finding as evidence that involuntary (exogenous) saccades are often not preceded by attention.

An alternative possibility is that exogenous saccades are always preceded by attention, but whether the change in gaze position reaches awareness depends on the speed of disengagement. It has been suggested that conscious awareness requires a certain degree of sustained allocation of attention (e.g. Most & Simons, 2001; Neisser, 1967). Therefore, it is possible that when attentional allocation on the location of the onset is too brief the erroneous saccade to the onset will not be perceived. Moreover, a number of studies have found evidence that attention and awareness can be dissociated (e.g. McCormick, 1997; Kentridge *et al.*, 1999; Lambert *et al.*, 1999).

Speed of Attentional Disengagement, Awareness and Oculomotor Capture

As an alternative to the view that in the anti-saccade task and oculomotor capture paradigm unperceived erroneous saccades to the onset are not preceded by attention, we propose that attention is always captured by the onset and whether the eyes move to the onset and whether these erroneous saccades are perceived depends on the speed of attentional disengagement from the location of the onset. This proposal is based on the following four assumptions. First, we assume that onsets capture attention, at least when attention is not already engaged on an object when the onset appears (e.g. Yantis & Jonides, 1990; Theeuwes, 1991). Second, erroneous saccades to the onset are only perceived when attention is directed to the onset for a sufficient amount of time. Third, attention is required at the saccade destination in order to program a saccade (e.g. Deubel & Schneider, 1996; Kowler *et al.*, 1995; Rizzolatti *et al.*, 1987). According to this assumption short fixation durations on the onset prior to a saccade to the target location (e.g. Theeuwes *et al.*, 1998, 1999; Mokler & Fischer, 1999) can only occur if attention shifts to the target location prior to the execution of the saccade to the onset. Furthermore, saccade programming will not be completed if attention disengages too soon. Fourth, shifts of exogenous attention are faster than shifts of endogenous attention (e.g. Theeuwes *et al.*, 2000). Therefore, in the oculomotor capture paradigm and the anti-saccade task the attention shift to the onset precedes the attention shift to the target location.

Given these assumptions these saccade behaviour and the awareness of the gaze position critically depend on the attentional capture by the onset and the speed of attentional disengagement from the location of the onset. If attentional disengagement from the onset is extremely fast, no saccade will be executed to the onset. In this case, attention will move from the onset location to the target location. Attention is then engaged on the target location for a sufficient amount of time to allow saccade programming to the target location. If attentional disengagement from the onset location is slower a saccade will be executed to the onset. These erroneous saccades to the onset can be distinguished on the basis of whether or not participants are aware of the erroneous saccade. This also depends on the speed of disengagement. Thus, when attentional disengagement from the onset location is relatively fast (but not fast enough to prevent an erroneous saccade) participants will not notice they moved their eyes toward the onset. If attentional disengagement is relatively slow participants will become aware of the erroneous saccade. Obviously, these are speculations which need to be tested in future research.

The Competitive Integration Model

Godijn and Theeuwes (in press-a, in press-b) developed a competitive integration model to account for the competition between exogenous and endogenous saccade programming. This model is primarily based on saccade behaviour from a variety of different tasks, but it also provides a framework within which the relationship between

attention and saccades and phenomenon such as IOR may be understood. We first discuss the assumptions concerning saccade programming and from there we turn to the control signals that precede the final saccade programming stage.

Architecture

The competitive integration model (e.g. Godijn & Theeuwes, in press-b, in press-b) assumes that exogenous and endogenous saccades are programmed in a single oculomotor system. Similar to a number of previous models (e.g. Kopecz, 1995; Findlay & Walker, 1999; Trappenberg *et al.*, 2001) the competitive integration model assumes that saccade programming occurs on a common saccade map, in which information from different sources (e.g. endogenous and exogenous) is integrated. Figure 1.2 illustrates the basic idea. Saccade-related activation at one location spreads to neighboring locations, but inhibits distant locations (Figure 1.2a). Thus, saccade programming is a competition between activations at locations represented in the saccade map. When two relatively distant locations are activated this activation is mutually inhibitory (Figure 1.2b), but when two nearby locations are activated, this activation is mutually excitatory (Figure 1.2c).

Temporal Trigger

It is assumed that a saccade is executed when a certain activation threshold is reached in the saccade map. In contrast to Findlay and Walker's (1999) model there are no separate "fixate" and "move" centers. Instead, the fixation location is part of the saccade map. Fixation-related activity is a critical aspect for the temporal trigger. When observers are actively fixating a specific location, the central portion of the saccade map is strongly activated (Krauzlis *et al.*, 1997; also see Kopecz, 1995). There is lateral inhibition between the fixation location and peripheral locations precisely like the lateral inhibition between distant peripheral locations. Therefore, when the fixation location is strongly activated this prevents the threshold from being reached at peripheral locations. When a saccade is required the fixation-related activation may be inhibited (typically referred to as oculomotor disengagement) releasing peripheral locations from the lateral inhibition from the fixation location.

Saccade Destination

The competitive integration model assumes that the saccade is directed to the mean vector of activity in the saccade map once the threshold is reached (e.g. Tipper *et al.*, 2000, 2001). Therefore, when other locations are activated when a threshold is reached, deviations of the saccade trajectory from the threshold location will occur. When two nearby locations are strongly activated the eyes will typically land somewhere between the two locations (e.g. Coren & Hoenig, 1972; Findlay, 1982; Godijn & Theeuwes, in

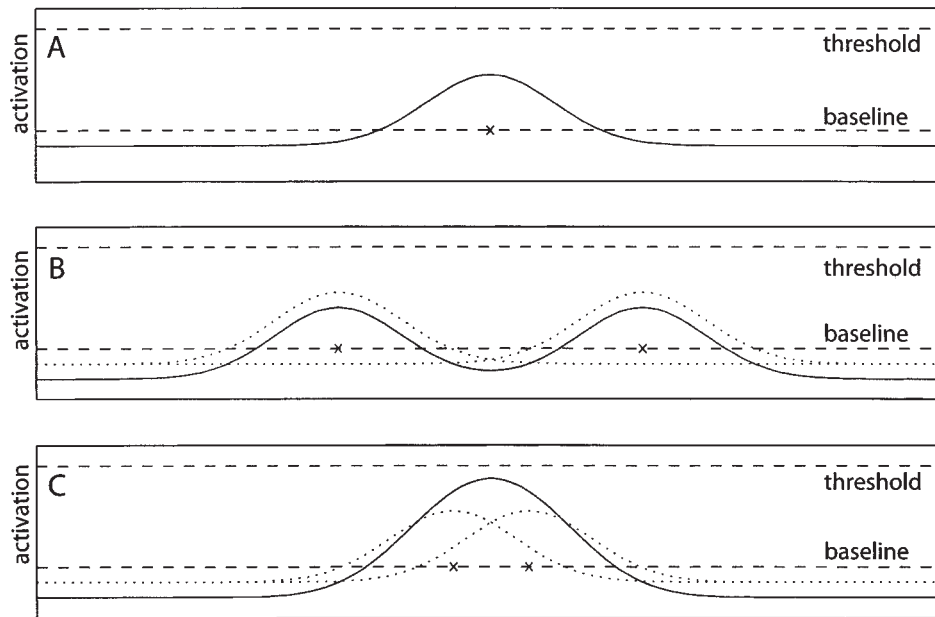


Figure 1.2: Activation patterns in the saccade map. (A) When a saccade is programmed to a certain location “x” in the saccade map, representing a location in the visual field, the activation spreads out to neighbouring locations, but inhibits distant locations. (B) When two saccades are programmed in parallel, activation related to both goals (the broken lines) is combined (continuous line) and when the two locations are relatively far apart activation is mutually inhibitory. (C) On the other hand, when two locations are relatively close together, the combined activation may result in a high activation peak somewhere between the two locations. From Godijn and Theeuwes (in press-b).

press-b). However, when two distant locations are strongly activated, the mutual inhibition will prevent the threshold from being reached.

Location-specific Inhibition

In order to execute a saccade to a target location, activation at other locations that are activated (e.g. the location of a task-irrelevant onset) needs to be inhibited. In addition to the lateral inhibition in the saccade map another inhibitory mechanism is assumed, which acts directly on the activation at a specific location (e.g. Tipper *et al.*, 2001). This allows the conflict between two locations to be resolved and biases saccade programming toward desired locations. This location-specific inhibition may result in a sub-baseline activation level causing the eyes to deviate away from the inhibited location (e.g. Tipper *et al.*, 2000, 2001; also see Doyle & Walker, 2001; Sheliga *et al.*, 1994, 1995), because the mean vector of activity will be shifted away from the inhibited location.

Attentional Control Signals

Before a saccade can be programmed to a specific location, control signals must be delivered to the saccade programming map. In a visual scene there are typically many potential targets for a saccade and therefore selection is required. In accordance with Schneider (1995) we propose that there is a common attentional selection mechanism for saccades and sensory processing. Thus, when an attentional control signal is applied to the saccade map in order to program a saccade the control signal is also applied to the visual system in which object features are processed (see also Chelazzi & Corbetta, 2000). Therefore, processing of object features is facilitated at the saccade destination. In addition, when a location in the saccade map is strongly activated, control signals may be applied to that location preventing the saccade. This inhibitory control signal is also passed on to that the visual system responsible for the processing of object features resulting in impaired processing of object features at the saccade destination.

Neural Correlates

The superior colliculus (SC) is typically considered the locus of the final stage of saccade programming (for reviews see Schall, 1991; Wurtz *et al.*, 2000; Sparks & Mays, 1981). The architecture of the SC is consistent with the competitive integration model (e.g. Olivier *et al.*, 1998; Munoz & Istvan, 1998) and it receives cortical input from a number of areas such as the frontal eye fields (FEF) and the lateral intraparietal region (LIP) in the posterior parietal cortex (PPC). It has been suggested that a fronto-parietal circuit involving these areas is responsible for delivering the control signal required for saccade programming (e.g. Chelazzi & Corbetta, 2000). Furthermore lesion studies have suggested that the FEF is involved in inhibiting saccades (e.g. Guitton *et al.*, 1985; Henik *et al.*, 1994; Rafal *et al.*, 2000). The LIP not only projects to the SC, but also to areas in the temporal and visual cortex, in particular IT and V4. Area V4 is specialized in processing object features, while IT is specialised in processing complex objects (Tanaka, 1993). According to LaBerge (1995) when a location is selected activation flows from the PPC to V4 and on to IT and enhances activation at the selected area while suppressing activation at surrounding areas. In the context of the competitive integration model it may be proposed that the attentional control signals arise from a fronto-parietal circuit including the FEF and LIP and are expressed in the SC for saccade programming and in visual areas such as V4 and IT in order to facilitate the perceptual processing at the selected location.

An Oculomotor Suppression Hypothesis of IOR

Within the framework of this competitive integration model Godijn and Theeuwes (in press-a) proposed an account of IOR based on oculomotor suppression. According to this account IOR is a result of a location-specific inhibition in the saccade map. This

inhibition is applied to a specific peripheral location in order to prevent the execution of a saccade. Furthermore, when a saccade is required activation at the fixation location is inhibited, releasing peripheral locations from the lateral inhibition from the fixation location. The location-specific inhibition causes a sub-baseline level of activation of the inhibited location. Within the framework of the competitive integration model the consequence of this inhibition is twofold: Subsequent saccades to the inhibited location are delayed (e.g. Abrams & Dobkin, 1994; Klein & MacInnis, 1999; Godijn & Theeuwes, in press-a). That is, it takes longer for the threshold to be reached at that location. Furthermore, saccade trajectories deviate away from previously inhibited location (e.g. Tipper *et al.*, 2000, 2001; Sheliga *et al.*, 1994, 1995; Doyle & Walker, 2001), since the mean vector of activity shifts away from the inhibited location. Figure 1.3 illustrates this idea. Shown is the saccade map representing activations that occur during a typical trial on which the eyes move to the target. At the start of the trial there is strong activation around the central fixation location (Figure 1.3a). After the presentation of the target display the fixation location receives top-down inhibition as the observer prepares to make a saccade (1.3b). Before the activation at the onset location can reach threshold target-related input reaches the saccade map and top-down inhibition acts on the location of the onset distractor (1.3d). Due to the inhibition at the location of the onset distractor the eyes move to the target, but with a slight deviation in the trajectory away from the onset distractor. If the activation at the onset distractor sets in too late to prevent the threshold from being reached at the location of the onset distractor the eyes first move to the onset distractor. If the activation of the onset distractor is inhibited shortly after the threshold is reached the saccade may fall short of the onset distractor and the reduced activation at that location will allow the threshold to be reached at the target location relatively quickly. This is consistent with the findings of Godijn and Theeuwes (in press-a, in press-b). In addition, subsequent saccades to the location of the onset distractor will be delayed (Godijn & Theeuwes, in press-a).

Relation to Other Models

Relations to Other Models of Saccade Programming

Previous models of saccade programming have typically assumed separate systems for the spatial and temporal aspects (“WHEN” and “WHERE”) of saccade control (e.g. Findlay & Walker, 1999; Becker & Jürgens, 1979). These models are consistent with findings from double-onset studies (e.g. Walker *et al.*, 1995, 1997; Ottes *et al.*, 1985; Lévy-Schoen, 1969). In these studies participants were required to execute a saccade to a target presented with an abrupt onset. On some trials an onset distractor was also presented simultaneously with the target. These studies showed that distractors that were presented near a saccade target affected the endpoint of the saccade, but not the latency, while distractors presented far from the saccade target affected the latency, but not the endpoint. Specifically, when a distractor was presented near the saccade

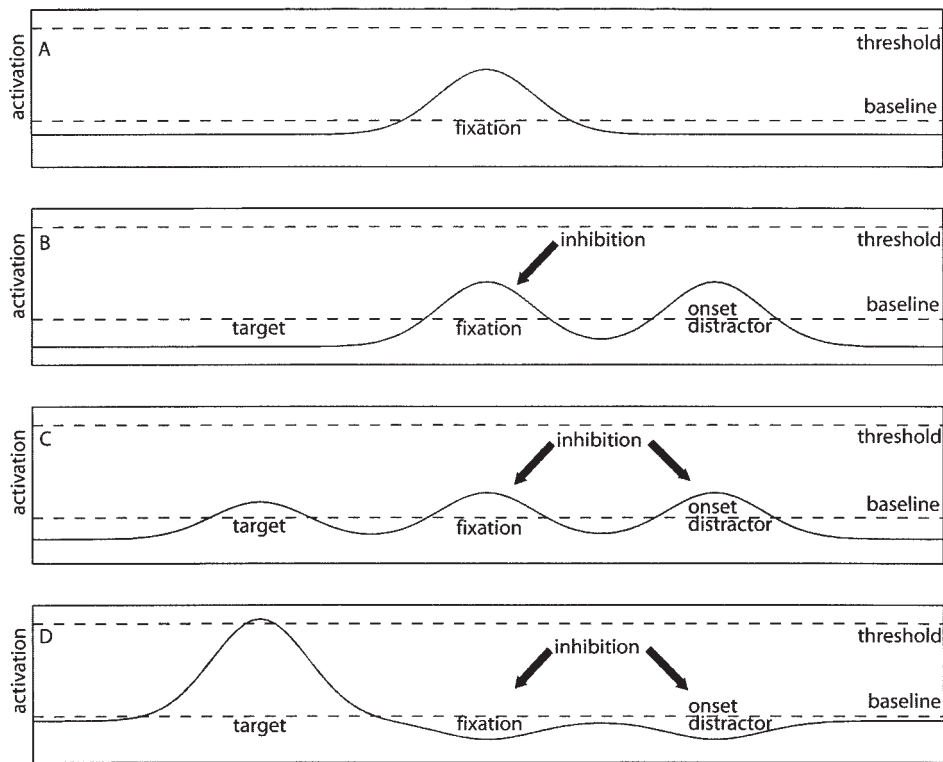


Figure 1.3: An illustration of the time course of activation in the saccade map according to the competitive integration model on a typical trial in the oculomotor capture paradigm. See text for details.

target the eyes often landed somewhere between the saccade target and the distractor (global effect; e.g. Coren & Hoenig, 1972; Findlay, 1982). However, when the distractor was presented near the saccade target the eyes often landed somewhere between the saccade target and the distractor was presented far from the saccade target the eyes moved to one or the other (no global effect), but with an increased latency relative to a no-distractor control condition (e.g. Walker *et al.*, 1995, 1997; Lévy-Schoen, 1969). According to models assuming separate WHEN and WHERE processes remote distractors affect the WHEN process, while neighbouring distractors affect the WHERE process (e.g. Walker *et al.*, 1997). Although the results of double-onset studies are consistent with models assuming a separation between the temporal and spatial aspects of saccade control, models in which the spatial and temporal aspects are integrated can also explain these findings. For example, the latency increase caused by distractors presented far from the onset target may be explained by the competitive integration model through its lateral inhibition architecture (see Figure 1.2b). Distractors presented close to the onset target do not increase latency, because there

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is mutual excitation between two nearby locations (see Figure 1.2c). Furthermore, a global effect is not found with far distractors, since distractor-related activity is inhibited in order to resolve the conflict between the target and distractor locations (see Figure 1.3). That is, the lateral inhibition between the locations prevents the threshold from being reached. Top-down inhibition of the distractor location is needed to release the activation at the target location from the lateral inhibition from the distractor location. When the threshold is reached the distractor location is no longer strongly activated so that no global effect occurs. The question remains how the competitive integration model can explain that saccade latencies are not reduced in double-onset studies on trials with a near distractor relative to trials without a distractor. Given the architecture of the competitive integration model one would expect such an effect, since the mutual excitation between two locations should allow the threshold to be reached faster than when no distractor is presented. However, as suggested by Ottes *et al.* (1985) participants may delay their saccade in order to prevent fast inaccurate saccades that land between target and distractor. Thus, it may well be that on near distractor trials the latency distributions are mixed; On some trials relatively fast global saccades are executed, while on other trials participants delay their saccade in order to prevent fast inaccurate saccades, resulting in relatively slow accurate saccades. The net effect would depend on the proportion of delayed saccades. In Ottes *et al.* (1985) all participants reported that delaying the saccade required a deliberate strategy. In the context of the competitive integration model a delay in saccade execution would be achieved by top-down activation of the fixation location. Due to the lateral inhibition from the fixation location activation at both the target and distractor location would be reduced, allowing more time for distinguishing between the target and distractor.

The competitive integration model of Godijn and Theeuwes (in press-a; in press-b) is similar to a number of other models that also assume a competitive integration structure (e.g. Trappenberg *et al.*, 2001; Kopecz, 1995; Findlay & Walker, 1999). Trappenberg *et al.* (2001) developed a neural model of saccade programming based on competitive integration of exogenous and endogeneous signals in the superior colliculus. Their model produced activity patterns very similar to activity patterns of cells in the superior colliculus. Furthermore, the initial saccade latencies of the model fitted well with a range of oculomotor effects. However, the model is only concerned with the initial saccade latencies and therefore does not account for effects on saccade amplitude, trajectories and fixation durations between saccades.

Modelling the Relationship Between Attention and Saccades

The competitive integration model assumes a strong relationship between attention and saccades. Whenever a location is selected as the goal for a saccade (exogenously or endogenously) perceptual processing of objects at the saccade destination is facilitated. Thus, there is a common attentional selection for the saccades and for object recognition. This is similar to Schneider's (1995) visual attention model (VAM). In this model selection is achieved in two parallel processing streams, a dorsal and a ventral stream. It is assumed that the dorsal stream (from V1 to PPC) selects information from

an object for actions, while the ventral stream (from V1 to IT) selects information from an object for recognition. Attentional selection occurs downstream in V1 and is passed through the dorsal and ventral processing streams. This selection is coupled to a single object. That is, when an object is selected, actions such as a saccades are programmed to that object and recognition of that object is facilitated. This does not mean that when attention is directed to an object a saccade is always executed towards it. It is assumed that a separate GO-signal is required for saccade execution.

Another model that assumes a strong relationship between attention and saccades is the premotor theory of attention of Rizzolatti and colleagues (1987, 1994). According to the premotor theory the mechanisms responsible for spatial attention are localised in the spatial pragmatic maps. Thus, attention shifts are accomplished by programming an action to a specific location. This is similar to VAM, but one major difference between the two theories is the direction of the causality: VAM assumes that a saccade program is a consequence of an attention shift, while the premotor theory assumes that programming a saccade causes an attention shift. Irrespective of the direction of the causality between attention and saccades, a one-to-one relationship between attention and saccades is predicted by both theories. That is, attention cannot be directed to an object without programming a saccade. Therefore, VAM and the premotor theory both represent efference theories of the relationship between attention and saccades (Posner, 1980).

Compared with VAM and the premotor theory the competitive integration model of Godijn and Theeuwes (in press-a; in press-b) is more concerned with the mechanisms responsible for saccade programming. First and foremost it is a model of saccade control. Although it is assumed that the control signals required for saccade programming are also applied to the (ventral) visual system, responsible for processing object features, the mechanisms responsible for object recognition are in its present form not specified. Future efforts in the development of the competitive integration model should shift the focus from the mechanisms responsible for saccade programming to the mechanisms responsible for object recognition.

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