ATTENTION CAPTURE BY MULTIPLE EVENTS USING DYNAMIC DISPLAYS

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Attention Capture by Multiple Events Using Dynamic Displays

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TABLE OF CONTENTS

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DECLARATION

I hereby confirm that I completed this thesis independently, that I have not heretofore presented this thesis to another department or university, and that I have listed all references used, and have given credit to all additional sources of assistance.

NOTE ON INCLUSION OF PUBLISHED WORK

Chapter 3 of this thesis has previously been published during the period of my PhD registration, and the copyright of this paper resides with the publishers (the reproduction of the paper as a chapter in this thesis is permitted in the terms of the copyright agreement. The paper is:

Sunny, M. M., & von Mühlenen, A. (2011). Motion onset does not capture attention when subsequent motion is "smooth." *Psychonomic Bulletin & Review*, *18*(6), 1050-1056.

Chapter 4 has been submitted to *Attention Perception and Psychophysics* and is under revision.

ABSTRACT

Being able to select relevant visual information from among irrelevant information is critical for the successful accomplishment of many day to day activities. However, the locus of attentional selection is not always under the control of the observer. Certain events and stimuli in the visual environment have been shown to control selection against observers' intentions and goals. These are said to capture attention in an automatic and stimulus driven manner. The events and stimuli that capture attention can be static (colour, shape, size, etc.) or dynamic (motion, flicker, etc.).

This thesis examines the effect of dynamic stimuli on attentional selection by using a visual search paradigm. The findings suggest that neither motion per se nor the onset of motion captures attention. They also suggest that when low refresh rate motion is used, capture occurs, but this effect cannot be attributed to capture by motion onset (Chapter 3). Further, the second study suggests that attention capture is observed using low refresh rate motion onsets because they are not masked as compared with the static items in the display. Thus capture is put down to a relatively better visual quality and stimulus encoding rather than motion (Chapter 4). The findings from this thesis also suggests that when back and forth oscillatory motion is used, capture re-emerges, but this effect is best attributed to a change in direction that happens to be temporally unique (Chapter 5). Another important finding is that in attention capture by abrupt onset, only one onset is prioritised in search (Chapter 6). The findings overall argue for a strong role of low level factors in attention capture by dynamic stimuli.

LIST OF TABLES AND FIGURES

Tables

Figures

Chapter 1: Introduction and Literature Review

[Attention] is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought […] It implies withdrawal from some things in order to deal effectively with others…

- William James (1890, pp. 403-404)

Introduction

Vision plays a very important role in our day to day life, guiding interactions with the outside world. As effortless as it may seem, the task of navigating through an ever changing and sometimes unpredictable environment is not easy. The visual and other perceptual systems have evolved over the years to efficiently deal with this seemingly difficult task. This efficiency is achieved by selecting only a small proportion of all the available information for further processing. The process by which selection of the relevant information is achieved is referred to as Attention. There are two broad areas of research in this domain that are important to the current thesis. The first concerns the stage at which attentional selection takes place and second concerns the actual mechanisms of selection.

With regard to the stage at which stimuli are selected for processing, there are two major views, the early selection view and the late selection view. The early selection view was proposed by Donald Broadbent (Broadbent, 1952, 1958) who studied how selection occurs during auditory processing. According to him, selection was necessary because of the severe capacity limitation faced by the faculty of higher processing. He used a dichotic listening task in which two different sets of messages were played to each ear and the participants were asked to shadow one of them (i.e., by repeating the message aloud while listening). In this task, it is assumed that attention was necessary to select information that is presented to one ear (or channel) while ignoring the other. Participants were then tested on different aspects of the information presented to the unattended channel. It was found that they were unable to report the semantic content of the messages, but could remember if the speaker was male or female. He proposed the filter theory, according to which stimuli are selected for higher order processing early in the processing stage. According to him, selection was based on the basic physical properties of the auditory stimuli like pitch, loudness etc. This view also suggests that the information that is not selected is not processed at all and is lost forever.

Other studies, however, attributed the findings from shadowing experiments to the time lapse between the shadowing task and testing (Glucksberg & Cowen, 1970; Norman, 1969), suggesting that the information might have been partially processed, but eventually forgotten. They suggested that attention was necessary to enable the transfer of information from the sensory register to long term memory. Thus, the early selection view considered attention as a filter that only let through relevant information while keeping out the irrelevant. Treisman (1960) extended the filter theory to account for the occasional failure of the attentional filter to keep back irrelevant information. According to her filter attenuation theory, the information that does not fit the filter is not completely ignored, but just attenuated, i.e., fewer resources are allocated to its processing. Thus the filter was set by assigning a lower threshold for the relevant stimuli as compared to the irrelevant. However, when a stimuli that is contextually relevant, like one's own name, is present in the attenuated stream, it automatically passes through the threshold and is processed. Neisser and colleagues provided further evidence for such exceptions to the attentional filter. Using a selective reading methodology, Neisser (1969) showed that even words that were frequently repeated often went unnoticed, whereas participants own names were picked up.

In contrast to the early selection view, the late selection view (Deutsch & Deutsch, 1963; Norman, 1969) proposes that all stimuli undergo a preliminary processing on their content, which aids in selection. The proponents of this view argued that there was no processing limitation until the level of categorization and that such limitation applies only to higher cognitive functions such as memory. Thus, they claim that attention is required only for the creation of a long term representation, and not processing. Even though the late selection view better explains the reason why some unattended information was later recognized and why unattended stimuli can often be processed up to a semantic level, it has not received as much empirical support as the early selection view (for example, see Lachter, Forster & Ruthruff, 2004). However, a redefinition of the mechanisms of attentional selection has made it possible to understand attentional selection in a more pragmatic way. For example, the concept of a pre-attentive stage (Broadbent, 1977; Neisser, 1967; Treisman, 1985) better explains some of the evidence favouring a late selection view.

Visual Search

Visual search has become one of the most commonly used paradigms to study visual selective attention. The general appeal of this paradigm is its relative simplicity that nonetheless allows for a detailed study of the mechanisms that underlie selection. In a visual search task, participants are typically asked to search for a specific stimulus (the target) in a display containing a number of other irrelevant items (distractors). The time taken to complete the search (Reaction Times or RT) and error rates are measured over a large number of trials. The basic assumption that defines the use of these measures is that RT is linearly related to the amount of information transmitted (Hick, 1952; Hyman, 1953). That is, given a perfect correlation between stimulus and performance, RT is assumed to increase by a constant for each additional unit of processing required and that the slope reflects the efficiency of processing. Thus, the difference in RT between two tasks that differ only on levels of processing is equivalent to the time it takes to complete the additional processing. Another advantage of the methodology lies in its versatility. As Nakayama and Martini (2011) point out, a wide range of stimuli (letter, numbers, faces, Gabor patches etc.) can be combined with a number of different features (colour, shape, size, contrast, movement etc.) to generate search displays. This versatility can be very helpful in dissecting the different processes involved in attentional selection.

There are several major theories of visual search. The most popular of them is the Feature Integration Theory (FIT) (Treisman & Gelade, 1980) which postulates that search proceeds in two distinct stages, the pre-attentive and the attentive. Treisman, Sykes and Gelade (1977) proposed that all the information was categorized based on primitive features like colour, shape, orientation, etc. at the pre-attentive stage. In FIT, Treisman and Gelade (1980) explain how visual search proceeds either in a parallel or in a serial manner depending on the relationship between the target and the distractors. They showed that the search for a target that is defined by a single feature (for example, determining if a red X is present among green Xs) can be accomplished at the pre-attentive level. That is, a spatial allocation of attention was not necessary for such a task. Such a search is also known as a feature search. In a feature search, RTs are not affected by the number of items in the display (display size). Thus, when RTs are plotted as a function of display size, they yield flat search slopes and search is considered to be parallel.

In contrast, when the target was defined by a conjunction of features (for example, a Red X among Green Xs and Red Os), search cannot be accomplished at the pre-attentive level as targets and distractors share common colour and form features. Hence, attention has to be allocated to the location of each object in a serial manner in order to find the target. Therefore, RTs increase as a function of display size in a conjunction search task, giving a steep search slope. According to Feature Integration Theory (FIT), the increase in slope reflects the additional level of processing that is required to find the target in a conjunction search task as compared to a feature search task.

Even though FIT offers a simple and elegant explanation of the visual search mechanism, there are many findings that do not fit within the framework of

FIT. For example, according to FIT, all conjunction searches should produce steep search slopes. However, many studies have shown that not all conjunction searches proceed in a serial manner. For example, a conjunction of motion and form was found to be more parallel than serial, and the addition of stereo depth enabled its conjunction with motion or colour to be parallel (McLeod, Driver & Crisp, 1988; Nakayama & Silverman, 1986; Steinman, 1987). These findings imply that, even for a conjunction target, the visual system is able to narrow search down to a relevant subset of features based on information available at the pre-attentive stage. Feature Integration theory cannot account for this finding.

The Guided Search Model (Wolfe, Cave & Frenzel, 1989) better accounts for the inconsistencies in the findings between FIT and findings from later studies. This model advocates that pre-attentive salience computations carried out during a conjunction search task can be effectively used to guide visual attention. In support of the GSM, they showed that a target defined by the conjunction of three features is found faster than a target defined by the conjunction of only two features. The revised models of Guided Search (Wolfe, 1990) specify that the role of parallel processing is to identify potential target locations. The information from the feature maps are used to create an activation map based on stimulus salience. The salience could be determined by both top-down and bottom-up components. A combined activation map gives an activation value of target probability for every location in which an object is present. Attention is deployed in the order of decreasing salience.

Thus, even though FIT assumes a strict dichotomy between serial and parallel search processes, other theories of attention have largely ignored such a dichotomy suggesting that pre-attentive salience computations can always guide attention. Attentional Engagement Theory (Duncan & Humphreys, 1989, 1992), for example, suggests that as the difference between targets and distractors increases, search efficiency also increases. According to AET, salience computations are used to segment parts of the display that are different from the rest. Duncan and Humphreys (1989) laid out two necessary conditions for an efficient search. First, the target should be different from the distractors in one dimension and second, the distractors should be more or less homogeneous in that dimension.

The theories of attention clarify the role of pre-attentive computations in the eventual guidance of attention. They specify the means by which information in the visual environment is registered by the visual system as its constituent features. Moreover, they also show how attentional processes can make use of this information to select objects for further processing.

Orienting of Attention

Before looking into the specific factors that determine salience of a stimulus, it is necessary to understand the different ways in which attentional control is exerted. The first of them is concerned with the goals and task set of the observer and the second with the specific features of the stimulus and the display (Posner & Snyder, 1975). The former is often referred to as top-down or endogenous control of attention, while the latter is referred to as bottom-up or exogenous control. Though in real life attention is allocated by a combination of these two factors, it is useful to separate them out in order to make the study of these mechanisms more efficient. Two major paradigms that are extensively used to study the orienting of attention are the cueing paradigm and the visual search paradigm.

Studies using the Cueing Paradigm

The orienting of attention proceeds endogenously when observers actively control the allocation of their attention to an object or location. Most of our goal-driven everyday behaviour, like driving or playing a sport, proceeds smoothly as a result of successful endogenous selection. In the classic study on endogenous cueing by Posner (1980), a central arrow cue was used to trigger attention to a desired location (See Figure 1.1). The nature of these cues is often considered symbolic because the cue in itself does not trigger attention to the location of the target. It is the assigned meaning of the cue understood by the observer that renders them meaningful. The cues could be arrows, words or digits, which inform the observer where the target will appear (Jonides, 1981; Posner 1980; Theeuwes, 1989). When the cue correctly points to the location of the target that follows, it is considered a valid cue and when it doesn’t, an invalid cue.

The effectiveness of an endogenous cue is determined by the overall informativeness or validity of the cue. When there are an equal number of valid and invalid cues (i.e., a cue validity of 50%) in an experiment, the cue is considered overall un-informative. Since the cue points to an incorrect location as much as it points to the correct, using the cue to guide search does not benefit performance.

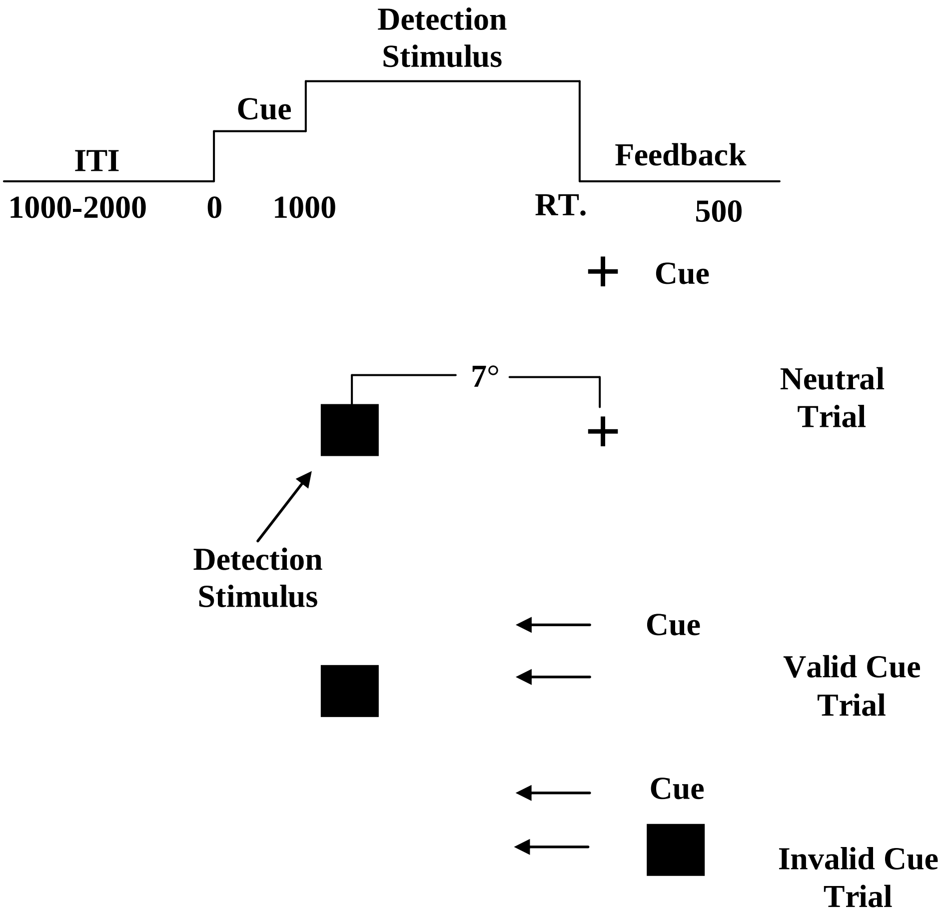

Figure 1.1. Example display taken from Posner (1980). The trials started with a central fixation cross. In a neutral trial, the central cue did not provide any information regarding the upcoming target. In the valid trial, the fixation cross changed into an arrow that correctly pointed to the target location, whereas in the invalid trial it pointed to a wrong location. The proportion of valid and invalid trials in an experiment determines the overall informativeness of the cue.

In contrast, when there are more valid cues than invalid cues in an experiment (for example, a cue validity of 80%), the cue is considered overall informative. That is, using the cue to guide search will result in correct selection more often than not. It was shown that when the cues are informative, valid cues benefit performance in terms of producing faster RTs and higher accuracy and invalid cues cost performance in terms of slower RTs and higher error rates (Jonides, 1981; Posner, 1980). This cost and benefit pattern between valid and invalid cues show that participants shift their attention to the location indicated by the cue.

Interestingly, when the cues are valid in a lesser proportion of trials (for example, at 20% cue validity), a reversal of the cueing benefit is observed; i.e., the target is detected faster in the invalid trials as compared to the valid trials. This further suggests that the performance benefit that occurs with an endogenous cue results from participants' internalisation of the information contained in the cue. They are able to actively decide whether or not they let attention be guided to a location based on the informative value of an endogenous cue. Moreover, even in the absence of explicit information regarding cue validity, observers are able to efficiently use or ignore a symbolic cue depending on its overall validity (Jonides, 1981; Müller & Rabbitt, 1989; Posner, 1980; Posner & Cohen, 1984).

Efficient guidance or capture is also mediated by the time interval between the onset of the cue and the onset of the target (cue-target-onset-asynchrony or CTOA). An endogenous cue requires a CTOA of at least 150 ms for it to be effective, reaching its maximum effectiveness at ~300 ms (Cheal & Lyon, 1991;

Jonides, 1981; Tsal, 1983). It has been suggested that it takes time for the participants to process the information contained in the cue and actively allocate attention based on this information.

However, attentional allocation is not always as straightforward or successful as it seems. Sometimes, events and stimuli in the visual field automatically draw our attention to themselves. Such a shift of attention that is automatic and inconsistent with, or against, the intentions of the observer is called exogenous control of attention. The stimuli that elicit such an involuntary orienting are said to have captured attention. Exogenous control has been extensively studied using luminance cues. The reflexive nature of the exogenous cue means that it affects performance even when the cue is uninformative of the target location; for example at a cue validity of 50% (Posner, 1980; Jonides, 1981).

As opposed to a central arrow, exogenous cues often consist of a brief luminance patch flashed in the periphery near a possible target or distractor location. The presentation of the cue is followed by target presentation, either at the same location as the cue (valid cue) or at a different location (invalid cue). Independent of cue validity, valid exogenous cues lead to an improvement in performance (in terms of faster RT and better accuracy) while invalid exogenous cues lead to a cost, when compared with neutral cues. This suggests that the cue involuntarily (automatically) draws attention to its location, giving an RT advantage in detecting the targets that appears immediately at that location and a disadvantage in detecting a target that appears at a different location (Jonides, 1981). This RT cost is attributed to the additional time it takes to disengage attention from the cued location, and allocate it to the target location.

Even though exogenous cues are thought to capture attention, complete automaticity of any mental process is established using three criteria – first, minimal use of mental resources; second, resistance to suppression; and third, lack of sensitivity to changes in expectancy (Hasher & Zacks, 1979; Shiffrin & Schneider, 1977). Jonides (1981) tested the automaticity of attentional allocation using both endogenous and exogenous cues. He asked participants to determine the presence of L or R among other letters of the alphabet. Both types of cues were valid on 70% of the trials and invalid on 30%. The performance in the search task was analysed over three different experiments that manipulated load, suppressibility and cue-validity. He found that an additional memory task interfered with the effectiveness of the symbolic cue, but not the peripheral cue, suggesting that the exogenous cue use little mental resources.

However, when the cues were un-informative, the endogenous cue was easier to ignore than the exogenous (peripheral) cue, suggesting that exogenous cues are processed automatically. In addition, while changes in overall cue validity affected the effectiveness of the endogenous cue, they did not have an effect on the effectiveness of the exogenous cue. Overall, the results suggest that exogenous cues capture attention reflexively, against the goals of the observer and are more immune to suppression than central cues. Later studies have shown that exogenous cues capture attention even when observers are not consciously unaware of the effect of such cues (Danziger, Kingstone, & Rafal, 1998; McCormick, 1997).

Further emphasizing the reflexive nature of the exogenous cue, it has been shown to have a shorter time course of activation as compared to endogenous cues (Jonides 1981; Muller & Rabbitt, 1989; Posner, 1980). Peripheral luminance cues can affect performance with a CTOA as short as 25 ms, reaching their maximum effectiveness at ~100 ms. The slow rising benefit in performance that comes from the symbolic cue is more sustained as compared to the peripheral cue (Cheal & Lyon, 1991).

Endogenous and exogenous cues have differential effects on attentional engagement and inhibitory mechanisms (Posner & Cohen, 1984). For example, a peripheral exogenous cue with a longer CTOA (> 300 ms) leads to faster RTs with invalidly cues targets as compared to validly cued targets. This phenomenon is known as Inhibition of Return (IOR). IOR with central cues follows a significantly slower time course (typically only after about 600 ms). This and other differences (for example, see Briand & Klein, 1987; Funes, Lupiáñez, & Milliken, 2007; Klein, 1994) between the two types of cues clearly suggest that they are separate mechanisms of attentional control (Briand & Klein, 1987; Friedrich, Egly, Rafal, & Beck, 1998; Muller & Humphreys, 1991), one controlled by the observer, while the other by the stimulus features.

Even though the spatial cueing task offers an excellent paradigm to study automatic orienting, it is limited by the types of cues that automatically attract attention. For instance, the most common peripheral cue is a luminance flash and thus one can say that luminance cues capture attention. However, using a cueing paradigm, it is difficult to estimate the different features that might capture attention. Moreover, some symbolic cues, like a gaze cue or a central arrow cue have been shown to elicit automatic responses (Friezen & Kingstone, 1998; Ristic & Kingstone, 2006). Thus, using a cueing paradigm one cannot clearly separate top-down and bottom-up effects. In such instances an entirely different paradigm might be required to determine the nature of purely bottom-up capture of attention.

Studies using the Visual Search Paradigm

In contrast to the cueing paradigm, a visual search paradigm offers more flexibility in the type of stimuli that can be tested for attention capture. For example, using a visual search paradigm, it is possible to test the attentional effects of colour changes, motion or the sudden appearance of a new object among old objects (abrupt onset) etc. (Jonides & Yantis, 1988; Hillstrom & Yantis, 1994; Theeuwes, 1990). The visual search paradigm also enables pitting different types of stimuli against each other, like an object that starts moving (motion onset) and an abrupt onset (Christ & Abrams, 2008).

The research on stimulus-driven attention capture has been primarily driven by two types of feature singletons (also referred to as feature discontinuities) – dynamic and non-dynamic. When an object differs from all the other objects in a display by a single feature, it can be considered a feature singleton. The non-singletons may or may not be different from each other in another dimension. For example, a red circle among other circles which are all green is a singleton in the dimension of colour. Even when the green coloured objects have different shapes, the red circle is a singleton in the dimension of colour.

A singleton is also conceptualised as a discontinuity of a feature by emphasising that pre-attentive salience computations will prioritise the singleton because it is different from the other items in the display. Singletons that are defined as a discontinuity of non-dynamic object properties like colour, shape, size or luminance can be categorised as static singletons. Some feature discontinuities are dynamic in nature. For example, singletons that are defined as moving among stationary or vice-versa; or by the sudden appearance or disappearance of objects in the search space; or by transient luminance changes like flicker can be considered dynamic discontinuities (for example, see Pinto, Olivers & Theeuwes, 2006).

Most of the theories of search (Duncan & Humphreys, 1989; Treisman & Gelade, 1980; Wolfe, Cave & Frenzel, 1989) would predict that a feature singleton can be efficiently detected at the pre-attentive stage. The salience computations at the pre-attentive stage would indicate a feature singleton to be the most salient item in the display. Thus, when participants are required to determine the presence or absence of a feature singleton, it will decidedly lead to flat search slopes. However, such a task reflects an endogenous or top-down control, driving attention in line with task demands. In order to be considered attention capture, a feature singleton should produce a flat search slope even when it is irrelevant to the search task.

Irrelevant Singleton Paradigm. In the experiments that use a visual search task to study attention capture, task irrelevance of the feature singleton is ensured using what is known as a *1/d paradigm*. In a *1/d paradigm*, the probability of the feature singleton being the target is a function of the display size (*d*). That is, in a display with 5 items, the singleton will be the target only on 20% of the trials (i.e. in only *1/5* trials and in a display with *d* items, only *1/d* trials). The *1/d* paradigm ensures that a flat search slope indicates bottom-up capture and not efficient guidance resulting from top-down strategizing. Most studies using this paradigm make use of a search task where attentional guidance is difficult. For example, Yantis and Egeth (1999) had participants search for a vertical bar among bars slanted at an angle of 30° in either direction of the target. In the first baseline experiment, they showed that such a search proceeds in a serial manner. This was indicated by RTs that increased as a function of display size.

In three other experiments, they examined how a colour singleton that was either predictive or non-predictive of the target affects search times for a target defined by orientation. A colour singleton was either present or absent, but when present it always coincided with the target making it fully task relevant. Unsurprisingly, in this condition search yielded flat search slopes for both the target absent and the target present conditions. However, when the target coincided with the singleton only at chance level (*1/d*), a positive slope was observed for RTs in both singleton and non-singleton target conditions.

This speaks against automaticity, showing that irrelevant colour singleton fails to capture attention in a purely bottom-up manner. They also showed a similar pattern for a singleton defined by motion, demonstrating a failure to capture attention. However, search was efficient when the target was either a size or a luminance singleton. The sensitivity of the search task to the overall probability of a singleton being the target or not speaks in favour of a top-down determinant in allocating attention and not bottom-up capture.

Other studies that have used the irrelevant singleton paradigm also failed to find evidence supporting purely stimulus-driven attention capture with many types of feature singletons. For example, Folk and Annette (1994) varied the feature contrast between the irrelevant singleton and the rest of the display (by adding texture to the display to decrease the contrast and comparing it with trials with no such texture) to examine if this mediates attention capture. They did not find a reduction in search slopes even when there was a background texture.

The results suggest that even though feature discontinuities that are defined locally may affect guidance, they do not capture attention. Other studies showed that motion, shape and colour singletons that were irrelevant to search did not capture attention (Hillstrom & Yantis, 1994; Lamy & Tsal, 1999). However, abrupt onset singletons captured attention, and motion captured attention when it indicated the appearance of a new object, suggesting a special role for new objects in attention capture.

In summary, the findings from the irrelevant singleton paradigm suggest an asymmetry in capture by both dynamic and non-dynamic feature singleton. For example, a size, luminance or abrupt onset singleton might capture attention while a colour and motion singleton does not (Jonides & Yantis, 1988; Theeuwes 1990). These findings also suggest that the various feature dimensions may be processed differently by the visual system, hinting at more than one mechanism to process local featural differences.

Additional Singleton Paradigm. Even though the *1/d* paradigm ensures that the singleton does not predict the target location, it still coincides with the target in some trials. Thus, even though the singleton status is irrelevant to search, the singleton is still a relevant object in the search context. Hence, for a search that proceeds in order of salience, it might make sense to start the search with the singleton even though it does not reliably predict the target. In other words, even though it might be more efficient to ignore the singleton status of an object in a search display, it might be easier to start searching with the salient item, especially since it could be the target on some of the trials.

A stricter criterion to determine capture by a singleton would be to use a paradigm where the singleton is never the target. In such studies, the singleton is presented only on a proportion of the trials and is never the target. The capture effect of such a singleton is indicated by an increase in RT when it is present as compared to when it is absent. This increase is attributed to the singleton capturing attention. Moreover, the information available after salience computations might specify only the presence of a singleton, but not specify the particular dimension along which this singleton is defined. In such cases, the interference from the singleton might be strong even when it is irrelevant for search. Conversely, if two dimensions can be processed independently, then one might expect little interference by a singleton in an irrelevant dimension.

Pashler (1988) tested the extent to which two dimensions can be processed separately. He tested whether features that varied along an irrelevant dimension produce interference and if so, how much of it depends on participants' knowledge about the identity of the target. He asked participants to determine the side of the display on which a feature singleton appeared. In four experiments, he used the dimensions of shape and colour and looked at how the pre-knowledge of one dimension (the target dimension) interacted with the homogeneity or heterogeneity of the other dimension (the distractor dimension). He found that prior knowledge of the identity of the target had no significant effect on the detection of a singleton target in spite of a random variation in an irrelevant dimension.

In other words, there was no interference from an additional singleton in an irrelevant dimension when the identity of the singleton was known in advance. This suggests that the visual system is able to efficiently segregate the different feature dimensions at a pre-attentive level. However, significant interference was observed when a singleton distractor in the irrelevant dimension was present, whose identity was not known in advance. Even though the study did not directly measure attention capture, the results suggest that often, when searching for a singleton target, the presence of other singletons in the display is likely to interfere with efficient attentional allocation, leading to a performance cost.

The additional singleton paradigm measures the cost of having an additional singleton in an irrelevant dimension on search. For example, Theeuwes, (1990) used search displays where the target was defined and reported along separate dimensions. This arrangement ensured that participants had to attend to the location of the target to make a response (Bravo & Nakayama, 1992; Duncan, 1985; Mounts & Melara, 1999). Participants searched for a left or right oriented 'T' among H).

The response was based on the direction in which the T was pointed. Additionally, the targets and the distractors were presented inside either a unique or a non-unique surrounding defined either by shape (Experiment 1) or by colour (Experiment 2). The probability of the target being inside a singleton was only at chance. In the control condition, however, the singleton always predicted the location of the target. The results showed that colour and shape singletons (as defined by the unique surround) failed to capture attention when they were irrelevant to the search task (Expt. 1 & 2), but when they served as a reliable cue (Control), they captured attention. In two further experiments, he tested if a unique change leads to capture. He used the same stimuli as in Experiment 1 and 2, but now the unique surround changed to a non-unique surround 250 ms after the onset of the search display. He found that only an abrupt change in shape tends to yield flat search slopes, not an abrupt change in colour.

Theeuwes (1991a, 1992) further examined the attentional effects of features when they belonged either to the relevant or to the irrelevant dimension (See Figure 1.2). Participants were required to discriminate the orientation of a line segment that was presented inside a predefined singleton (again, defined by the surround) target. The target would consistently be presented in a singleton defined by a specific dimension (colour, luminance etc), but the specific feature (red, green etc if the dimension was colour) varied randomly from trial to trial.

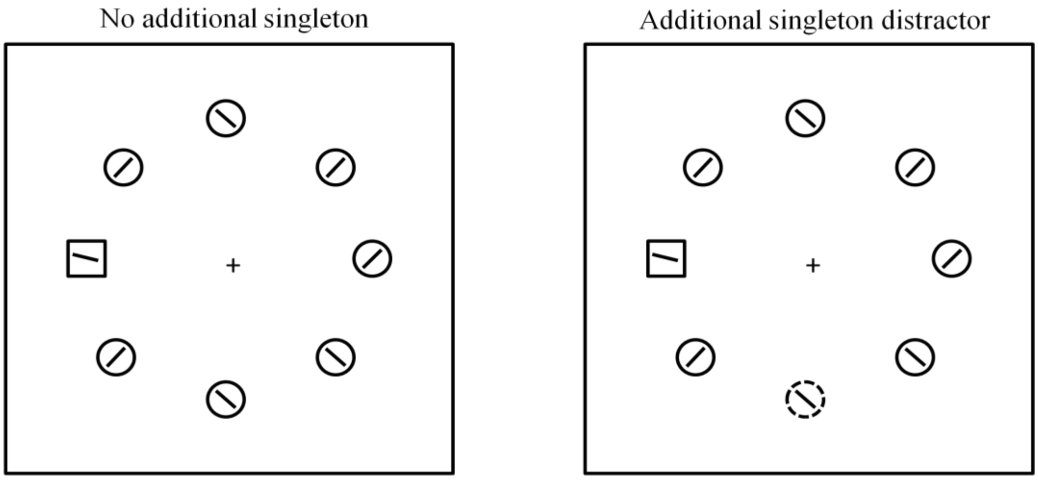

Figure 1.2. Example of the display using additional singleton paradigm in which a shape singleton defines the target. In the left panel, there is no additional singleton, but in the right panel there is an additional singleton (represented by the dotted circle –a colour singleton).

For example, in Experiment 1, the line segment was presented in either a bright singleton among dim distractors or in dim among bright; or in green coloured singleton among red distractors or in red among green. The specific colour or luminance varied from trial to trial, but the dimension along which the singleton was defined was kept constant. (In Experiment 2, the target could be a circle among diamonds or vice versa.) Importantly, in some of the trials, an additional singleton in an irrelevant dimension would be presented (i.e., when shape was the relevant dimension, one of the distractors would randomly be a colour singleton). The target was always presented in the relevant singleton.

He found strong interference by a colour singleton distractor when searching for a form singleton target, but not vice versa. Additionally, this interference from an irrelevant singleton occurred when the irrelevant dimension was overall more salient than the relevant dimension, but not when it was less salient (i.e., when a shape singleton was presented as an irrelevant distractor singleton, it interfered with search only when the targets and distractors were less salient colour singletons like yellowish red vs. yellowish green making the dimension of form overall more salient than the dimension of colour). He also showed that this bottom-up capture did not go away with increased practice (Theeuwes, 1992). These results suggest that attention capture is strongly salience based and thus stimulus-driven. The persistence of capture in spite of training suggests a robust effect that cannot be easily controlled in a top-down manner. To summarize, the findings from the additional singleton paradigm shows that a saliency map supersedes any top-down featural prioritisation during attentional allocation.

The role of the Attentional Window in capture

Capture in an additional singleton paradigm is modulated by what is referred to as the size of the attentional window, suggesting that events and feature singletons capture attention when attention is spread across the display, but not when it is focused. Indeed, the idea that focused attention reduces distractor interference is not new. For example, LaBerge, Brown, Carter and Bash (1991) showed that distractor letters that appeared on either side of a central target letter (flankers) interfered less with target detection when participants were in a focused attentional state. Many later studies have shown that singletons do not capture attention when attention is focused at a location (Belopolsky, Zwaan, Theeuwes, & Kramer, 2007; Theeuwes, 1991; Theeuwes, van der Burg, & Belopolsky, 2008; Yantis & Jonides, 1990). For example, Yantis and Jonides (1990) used a endogenous cueing task with 80% cue validity. In some of the trials, an abrupt onset was also shown in the display. If the onset captured attention in spite of the intention of the observer to attend only to the cued location, it suggests that capture by onsets is highly automatic. However, they found that abrupt onsets failed to capture attention when attention was already allocated to another location.

Although this finding argues against true bottom-up capture, it is possible that the interrupt signal generated by the appearance of an abrupt onset item was not strong enough to interfere with search when attention was focused elsewhere. Thus, when the interrupt signal associated with an onset is stronger, it might capture attention. To test this, Yantis and Jonides (1990) used a paradigm that allowed some degree of target interference (e.g., see Eriksen & Schultz, 1979; Yantis & Johnston, 1990). Every trial had a display size of three with two of them named as target letters. One of two target letters was pre-cued using a central arrow cue and participants were asked to base their response on the cued target letter. On half of the trials, the cued target had an abrupt onset whereas on the other half, either the un-cued target or the distractor had an abrupt onset. They found that the presence of an un-cued target slowed reaction times, irrespective of whether it had an abrupt onset or not. This suggests that when attention is already focused on a particular location, an onset does not capture attention.

A better comparison between top-down control and bottom-up capture could be obtained when the onset is presented before such an attentional state is maintained. Theeuwes (1991b) compared the effect of the central cue-display onset asynchrony and peripheral cue-target onset asynchrony on attention capture by abrupt onsets and offsets. He used three central cue-to-target onset asynchronies (CTOA) (-600, -300 and 200) and four peripheral onset or offset CTOA (-160, -80, 0 and 80) and found that abrupt onsets did not capture attention when attention was already focused elsewhere in the display (-600 and -300). However, when attention was distributed (200 ms), search consistently started at the location of the onset. Additionally, irrespective of the CTOA after which the onset stimulus was presented, abrupt onsets failed to have an attentional effect under focused attention.

Some researchers have viewed this as evidence for top-down set for location and the finding is often interpreted as an instance where top-down control can successfully override bottom-up capture of attention (for example, see Folk and Remington, 1999). However, evidence has also accrued in favour of capture even when attention is spatially focused. For example, Neo and Chua (2006) showed that abrupt onsets capture attention even under focused attention, as long as the onsets are an infrequent event. Moreover, Folk, Leber and Egeth (2002) showed that when participants were engaged in an RSVP (a Rapid Serial Visual Presentation task in which individual visual stimuli are presented very rapidly in the same spatial position, and participants are asked to detect a target stimulus defined by a certain feature like a red letter among green distractor letters) task where the target was defined as a colour singleton, an irrelevant colour singleton presented in the periphery caused an attentional blink to a subsequent target. This has been interpreted as attention capture by the irrelevant singleton. However, a central distractor designed to engage attention in the RSVP stream prevented subsequent capture by a distractor in the periphery. Thus, they argued that rather than having a focused attentional state, attentional engagement is necessary for overriding bottom-up capture (Folk, Ester, & Troemel, 2009).

Top-down effects on attention capture

Contrary to the claim of Theeuwes (1991, 1992) that capture is entirely determined by bottom-upsalience computations, Bacon and Egeth (1994) showed that top-down control can prevent bottom-up capture. They suggested that observers could choose one among two search modes, depending on how much they know about the target. This idea is also supported by the findings from Pashler (1988) that there is little interference when searching for a known target (red circle), as compared to an unknown target (a colour singleton circle). Bacon and Egeth (1994) suggested that knowing the specific feature enables observers to tap into the feature map to detect the target, resulting in little interference from a singleton in the irrelevant dimension. However, when the specific feature is not known, they have to rely on pre-attentive salience computations to detect the singleton in the display. In such a scenario, another salient item in the display is more likely to capture attention. They called the former type of search a feature search mode and the latter a singleton detection mode. These two search modes might be inherently top-down or bottom-up. That is, in a feature search mode, participants are intentionally looking for a known target and they are successful, whereas in a singleton detection mode, they have to rely on the information from the stimulus to guide their attention.

Bacon and Egeth (1994) further showed that participants could be forced to do a feature search in a task where they would otherwise engage in singleton detection. They did this by making the relevant feature a non-singleton and then by having singleton distractors defined in the irrelevant dimension. These ensured that a singleton detection mode was not sufficient to detect the singleton target in an efficient manner. An efficient search was possible only by adopting a feature search mode. The results suggested that there was cross-dimensional interference (e.g., interference by a colour singleton when the relevant feature is shape) only under a singleton detection mode, but not under a feature search mode.

However, Theeuwes (2004) suggested that results of Bacon and Egeth (1994) could be confounded by the use of a heterogeneous display which reduces the salience of the singleton and might not reflect the adoption of a different search strategy by the observers. He showed that the capture effect could reappear by increasing the saliency of the singleton in the displays used by Bacon and Egeth (1994). In summary, Theeuwes and colleagues use the findings from the additional singleton paradigm to propose a model which argues that when attention is diffused, visual selection is completely stimulus-driven and that successful top-down control, when it occurs, is a result of a massive recurrent feedback processing that overrides the stimulus-driven selection (see Theeuwes, 2010, for a review).

Contingent Involuntary Orienting

Further evidence of top-down influence on attention capture was proposed by the contingent involuntary orienting hypothesis (Folk, Remington & Johnston, 1992; Folk, Remington & Wright, 1994). According to the contingent capture account, capture is always goal driven. Contingent capture studies make use of a pre-cueing paradigm where a feature cue was presented at the location of the target, either matching with the target feature or not. Within a block, the cue was either 100% valid or 100% invalid. It was found that when the search display is preceded by an irrelevant colour cue, colour captured attention and an onset did not; when the cue was an onset, the capture effect was reversed – an irrelevant onset captured attention, colour did not. This was also found to be true for a motion cue. That is, when there is more than one feature discontinuity, one of which is relevant, it interferes with selection.

The results suggest that attention capture by a particular feature is contingent on the relevance of the feature to the task at hand. That is, if the observer is required to constantly monitor a certain type of feature discontinuity in order to efficiently detect the target, then such a discontinuity will capture attention. This proposition is somewhat similar to that of Bacon and Egeth's

(1994) search modes and speak in favour of capture being determined by top-down goals of the observer. The use of the pre-cueing paradigm have made it difficult to determine if the absence of capture for a non-matching cue in fact results from the inability to transfer the attention from the cue to the target (see Rauschenberger, 2003 for an analysis between capture effects using auto- and allo-cues). Others have suggested that the CTOA of 150 ms that is generally used in the pre-cueing studies make it difficult to measure the capture effects, if quick disengagement follows (see Theeuwes, Olivers & Belopolsky, 2010, for this and other difficulties posed by the paradigm and other interpretations of their findings).

The debate about selection being stimulus-driven or goal-driven is far from being resolved. More recently, it has been argued that the interference from an irrelevant additional singleton results from non-spatial filtering costs and does not reflect attention capture (Folk, Remington & Wu, 2009; Wykowska & Schubö, 2011). However, other studies have shown that this might not be the case (Schreij, Theeuwes & Olivers, 2010). In spite of differences in paradigms and interpretations, certain factors are known to have a strong mediating power on stimulus driven capture. The most important of them is the extent of attentional focus and the time course of selection. Other factors that could influence capture includes the perceptual load and uniqueness of a dynamic change (Cosman & Vecera, 2009, 2010; von Mühlenen, Rempel, & Enns, 2005)

Attention Capture by Dynamic Discontinuities

Abrupt Onsets

A dynamic singleton that is quite robust in its attentional effects is an onset singleton (i.e., the sudden appearance of a new object among old objects). Many electrophysiological and psychophysical studies in the early 1970's showed that the visual system is differentially sensitive to transient and sustained visual events like abrupt onset and offset or relative motion (Fukada & Saito, 1971; Cleland, Levick, & Sanderson, 1973; Kulikowski & Tolhurst, 1973; Tolhurst, 1975). Yantis and Jonides (1984) systematically tested the attentional effects of an abrupt onset as compared to a gradual onset. They adopted the so-called 'no-onset procedure' as described by Todd and van Gelder (1979). In their study, the search display was preceded by a preview display that consists of figure-8 place-holders (an object that is made up of 7 line segments, that looks like a digital 8; letters of the alphabet can be made from these by removing corresponding line segments) for a short time (1000 ms) (see Figure 1.3). Then, the irrelevant line segments from the figure-8 stimulus are gradually removed (gradual onset) to reveal the search display.

Simultaneously with the gradual onset, Yantis and Jonides (1984) added a new stimulus to the display, which now had an abrupt onset compared to the gradual onset of the other stimulus. The abrupt onset stimulus was as likely to be the target as the gradual onset stimuli, making the 'onset status' of the stimulus irrelevant to search. They also used stimuli which shed the line segments abruptly rather than gradually (referred to as no-onset stimuli).They found that the RT to find an abrupt onset target was unaffected by changes in display size, suggesting that attention is automatically allocated to an abrupt onset in spite of the onset feature being irrelevant to the search task.

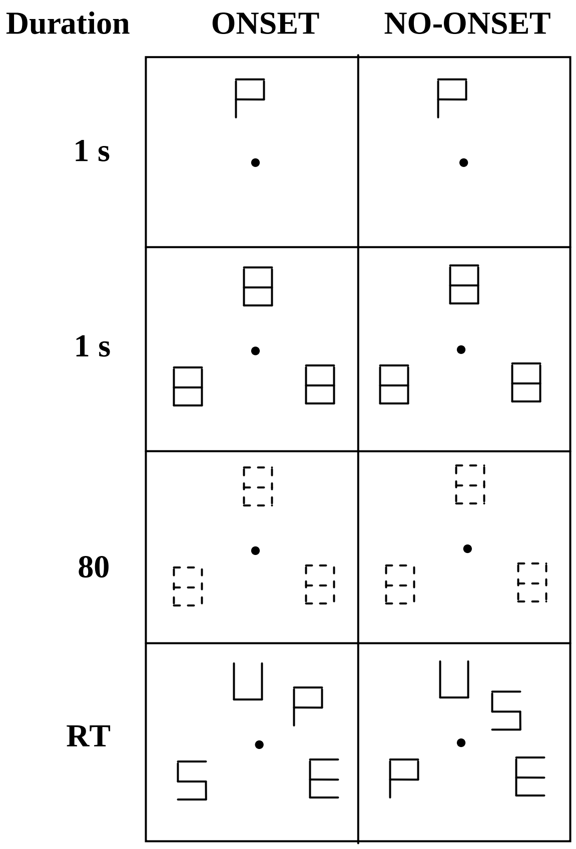

Figure 1.3. Example display taken from Yantis and Jonides (1984), for display size 4 and with gradual and abrupt onset stimuli. Participants are first informed of the identity of the target. The place-holder display is presented for 1000ms, which then gradually changes to letters over 80ms. An abrupt onset letter is added to the final display. Dashes represent fading line segments. In the above example, the target letter is P and in the onset condition, is an onset while in the no-onset condition, it is not.

As far as abrupt onsets are concerned, they capture attention as long as attention is not already focused on a target location. They have been tested extensively and are shown to fulfil all the three criterions of automaticity, vis-à-vis minimal use of mental resources, resistance to suppression and lack of sensitivity to changes in expectancy (Yantis & Jonides, 1988). However, the mechanism underlying the onset effect (i.e., the finding that onsets are prioritised over other objects) is a matter of some controversy. The most popular and the most tested is the new object account which proposes that the abrupt onsets capture attention because they signal a new object in the visual field.

New Object Account. The argument made in favour of the perceptual newness draws substantially from the concept of object files (Kahneman, Treisman & Gibbs, 1992). According to Kahneman et al. (1992), for every object that is perceived, a corresponding object file is created and maintained by the visual system. These object files are updated periodically and any changes that happen to an existing object are updated in the object file. Even though they do not make a strong claim as to whether attention is required for updating, they confer that the object files are automatically updated when attention is allocated to the object. In the context of abrupt onsets, it has generally been argued that the sudden appearance of a new object in the visual field requires the creation of a corresponding object file and that this automatically draws attention to the location of the new object (Christ & Abrams, 2006; Yantis & Jonides, 1990).

Early evidence for a special role of new objects in attention capture was given by Hillstrom and Yantis (1994). In their Experiment 1, they showed that motion can be used as an effective cue to guide attention when it is task relevant, but that an irrelevant motion does not capture attention. In Experiment 2, they tested the possibility that new objects that are not associated with an abrupt onset could capture attention. They used a global/local task (for example, see Navon, 1977) and asked participants to indicate the identity of the global letter. There was always a unique letter among the letters that made up the local level, which was either compatible or incompatible with the global letter. Moreover, the unique letter either had an onset, motion or in the baseline condition, neither of these. They found stronger compatibility effects when the unique letter was moving or had an abrupt onset as compared to the baseline condition.

When motion started before the letters were revealed, the compatibility effects disappeared, showing that only events associated with the appearance of a new object captured attention. Lending further support to the new object account, Christ and Abrams (2006) found that attention was captured involuntarily when an object was segregated from a group of objects. They used different types of motion, namely, motion onset, continuous motion, and motion offset and found that irrespective of type of motion used to segregate objects, a newly segregated target was found significantly faster (more than 100 ms on average) than a target that remained in the old group. This gives some support for a preferential processing of objects that undergo a higher level change than say changes to object properties like luminance, colour etc.

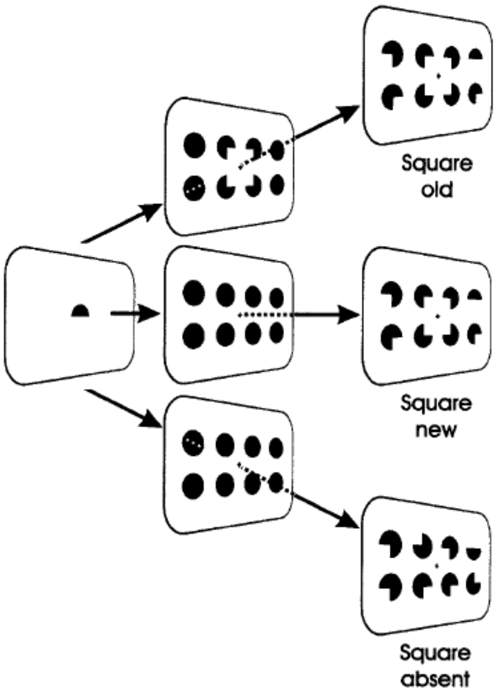

Figure 1.4. Example display from Rauschenberger and Yantis (2001). The subjective square was perceptually old, perceptually new, or absent. On half of the trials, the square was absent; on the other half, it was present. When present, they were either new or old with equal probability.

It has also been found that new objects captured attention even when such an object was illusory. Instead of using real objects, Rauschenberger and Yantis (2001) used 'pacman' shaped disc segments (See Figure 1.5) that could be arranged such that they resulted in the formation of an illusory square in the display (a Kanizsa square). Participants were asked to indicate the presence or absence of the target, a semi-circular disc segment. In some of the trials, the subjective square was presented at the beginning of the trial - along with the place-holders (which were black circular discs), making it an old object.

In some trials, they were presented along with the search display making it a new object, while in other trials there was no subjective square present. They found that only when the subjective square present in the display was new, it resulted in slower response times, but did not when it was old, suggesting that the perceptual newness of the illusory object captured attention. However, it has been shown that there is object precedence in search irrespective of its newness. For example, Yeshurun, Kimchi, Shashoua and Carmel (2009) showed that search performance was better when the target appeared inside the perceptual object than outside. This benefit did not go away when the target presentation was followed by display offset, suggesting that attention was allocated to the location of the perceptual object in an involuntary fashion.

In line with the idea of object files, Wong, Peterson and Hillstrom (2007) tested to see if changes in semantic or structural information were as efficient as an abrupt onset in producing an oculomotor capture. They used search displays that consisted of six uniquely shaped stimuli. Participants were asked to move their eyes to a colour singleton and make a response based on the direction in which the target 'c' presented inside was pointing. Simultaneous with target presentation, one of the two events occurred: There could be an abrupt onset in any random location in the display, or one of the unique shapes morphed into another (changed the shape over a sequence of frames).

There was also a control condition where neither of these happened. They found that, as compared to the control condition, participants were significantly quicker to detect the target when it was presented in either the abrupt onset or the morph. There was no difference in detection efficiency between the morph and the onset. However, when occulo-motor capture was measured, an onset reliably elicited an eye movement towards itself, whereas the morphs did not. This shows that although changes in semantic information could warrant attentional capture, they do not capture the eyes as reliably as an abrupt onset.

It has been well established that the eyes follow attention (Itti & Koch, 2001). Considerable evidence has accrued showing that abrupt onsets capture the eyes even when they are completely task irrelevant (Mulckhuyse, van Zoest & Theeuwes, 2008; Theeuwes, Kramer, Irwin & Zelinsky, 1999). For example, Theeuwes et al. (1999) asked participants to saccade to a colour/luminance singleton target. An abrupt onset distractor was also presented in the search display. They found that on a significant proportion of trials (30 to 40%), participants erroneously initiated an eye movement towards the onset.

Mulckhuyse et al. (2008) also pointed out that top-down and bottom-up factors work together to ensure efficient processing after the initial capture response. That is, quick disengagement is often efficiently executed after the erroneous oculomotor response (see also, Theeuwes, Kramer, Hahn and Irwin,1998). Furthermore, Kramer, Cassavaugh, Irwin, Peterson and Hahn (2001) examined the oculomotor effect of single or multiple onset distractors on a singleton search task. They observed that, even though an irrelevant onset distractor did not direct a saccade to its location, it interfered with search strategies and increased reaction times. They also found that having two abrupt onset distractors was no more disruptive than having a single onset distractor.

Yantis and Gibson (1994) suggested that 'newness' can be rather perceptual in the sense that when an existing object disappeared for about 100 ms and reappeared again it has the same effect as an abrupt onset. However, this does not agree with the findings of Kahneman, Treisman and Gibbs (1992) who showed that even a temporal gap of 590 ms between object fields did not interfere with object continuity. In spite of overwhelming evidence supporting the new object account, there have been criticisms.

Role of Luminance. The most prominent of the criticisms against the new object account is that an abrupt onset is accompanied by a large local increase in luminance, whereas the luminance decrease accompanying the transformation of figure-8 to letters is relatively smaller. For example, if a letter, say 'S' is introduced as an abrupt onset, it would involve the onset of 5 line segments that form the figure 'S', whereas if it is introduced as a no-onset, it would involve deletion of only two line segments from the figure-8. This asymmetry might make the onsets more favourable than the no-onsets. To circumvent this asymmetry, Miller (1989) used a place-holder display with more line segments that need to be deleted to reveal the letter, as compared to a typical figure-8 place-holder. This arrangement was helpful in matching the luminance change for the no-onset stimuli, with that of an abrupt onset. The results showed that, although an onset transient was detected ~36 ms faster than an offset, it was no longer insensitive to the load. As display size increased, it took longer to find the onset transient. The results suggest that when luminance changes are controlled for, abrupt onsets no longer reliably captured attention.

On a related note Miller (1989) pointed out that, instead of undermining the ability of an abrupt onset to capture attention, this finding indicates possible attentional effects of an abrupt offset. Watson and Humphreys (1995) however showed that abrupt onsets and offsets have equivalent effects on attention. They used stimuli with onsets or offsets, but without an accompanying new object (i.e., only part of the stimulus underwent offset or onset). They found that both onsets and offsets had very similar effects on search performance, suggesting that an increase or decrease in luminance does not differentially affect performance. The finding implies that as long as the overall change is kept constant, the direction of change does not affect attention.

In order to further differentiate between the effects of luminance changes and those of new objects, Franconeri, Hollingworth and Simons (2005) used a paradigm that made it possible to introduce new objects by removing any abrupt luminance changes. They used occluders that changed size (either expanded or contracted) and the abrupt onset could occur either behind the occluder or in front of the occluder. They found that abrupt onsets received an RT benefit only when it appeared in front of the occluder, but not when it appeared behind it. Thus it was shown that a luminance transient was necessary for an abrupt onset to capture attention.

However, the conclusion can be criticised on the basis of methodological uncertainties. For example, given that attention capture is sensitive to changes in object status even for a very short time frame (cf. Yantis & Gibson, 1996) it is possible that, along with removing the luminance transient, the occluder also changed the status of the place-holders as old objects, removing any difference between the old and the new. However, Chua (2009) used an occluder that hid the objects only for about 10 ms, likely removing any possible disruption to object continuity. Their findings closely resembled that of Franconeri et al., suggesting that luminance changes were necessary for onsets to capture attention. However, they also extended these findings to show that when the context facilitated the encoding of the new object, it captured attention. (See also Chua, 2011, where capture was observed when the encoding of the old objects was facilitated and absent when such an encoding was difficult or impossible.)

On the other side of the argument, a luminance transient was deemed neither necessary, nor sufficient, to produce capture by abrupt onsets and makes a strong argument in favour of the new object account (Yantis, 1993; Yantis & Gibson 1994; Yantis & Jonides 1994). For example, it has been shown that onsets capture attention even when they are equiluminant with the background (Davoli, Suzko & Abrams, 2007; Yantis & Hillstrom, 1994). Moreover, Gellatly, Cole and Blurton (1999) showed that when stimuli are matched in luminance to the background, the onset effect was considerably reduced, but not eliminated. Enns, Austen, Di Lollo, Rauschenberger and Yantis (2001) showed that the attentional effect of huge luminance changes does not compare to those produced by an abrupt onset. They used a visual search task to assess the effect of a change in luminance on capture by abrupt onsets.

The distractors changed from black to white or white to black on a grey back ground, while the abrupt onsets were either black or white. Hence, the change in luminance was larger for the luminance change stimuli as compared to abrupt onsets. Despite this, abrupt onsets were more effective in capturing attention. Even though these findings do not offer direct support for the new object account, it shows that the capture effect remains relatively unaffected even in the absence of luminance changes.

In summary, the case for luminance transients in attention capture by abrupt onsets is not a strong one. Even though matching stimulus luminance with the background leads to a reduction in the capture effect, it is not abolished (Christ & Abrams, 2008; Davoli et al., 2007; Gellatly et al., 1999). In contrast, when the appearance of the new object is hidden from the observer, onsets were treated as equivalent to a no-onset (Franconeri et al., 2005; Chua, 2009). From these findings, it is clear that low level luminance changes have a role in onset capture, but the appearance of a new object seems to have a bigger role.

Role of Masking. Another opposition to the new object account as an explanation of onset capture was provided by Gibson (1996a). He argued that in a standard display with an abrupt onset, the placeholders act as pre-masks, making the abrupt onset the only item that is not masked. Thus, the better visual quality of the abrupt onset leads to capture because it is better encoded and is available for processing before the no-onsets are. Participants were asked to find a predefined target letter among distractor letters. Gibson (1996a) used three different placeholder conditions – bright, dim and onset (no placeholder). In the bright conditions, the luminance of the placeholders was equivalent to that of the search display, while in the dim condition they had a lower luminance as compared to the search display. Finally, in the onset condition, there were no placeholders, so that all the elements in the placeholder condition had an abrupt onset. The final search displays were identical in all the three conditions.

The results showed that participants were fastest in the onset condition, followed by dim placeholder condition. The slowest RTs were found in the bright condition. In a second experiment, he combined bright and dim placeholders with either an onset or no-onset target. In the dim placeholder condition, onsets did not capture attention but strong capture was observed when the placeholders were bright. The results overall suggests that attention was automatically guided to the stimulus that had a better visual quality. However, Yantis and Jonides (1996) reinterpreted the advantage of an all onset display in terms of a faster processing associated with capture by onsets (see also Gibson (1996b), who provides further evidence for a masking explanation).

To summarize, the most popular explanation of capture by onsets is given by the new-object account, according to which onsets are prioritised because they initiate the creation of object files (Hillstrom & Yantis, 1994). However, this explanation is not without criticisms. One alternative explanation is that a local change in luminance is what triggers attention and that without such a change abrupt onsets might not capture attention (Franconeri, Hollingworth & Simons, 2003). However, it has been shown that even though controlling for luminance changes reduces the onset effect, it is not abolished, suggesting that capture is not all driven by the luminance changes (Gellatly, Cole & Blurton, 1999). Yet another explanation of the onset effect was given by the masking account (Gibson, 1996a). Even though evidence has been provided suggesting that this explanation is unlikely, it is disputable (Gibson, 1996b; Yantis & Jonides, 1996).

Motion and the Onset of motion

A moving object among other stationary object represents a dynamic discontinuity that might capture attention. One of the earliest studies that made use of motion as a feature in visual search was conducted by Nakayama and Silverman (1986). They examined if the conjunction of a static feature like colour and a dynamic feature, like motion also resulted in a standard serial search. They used two different colours and two different motion directions, combining a particular colour with a specific direction of motion. The target was defined as the item that violated this association. The results from this study showed that such a conjunction resulted in a particularly difficult serial search because search slopes increased with increasing display size. However, when they used a stereoscopic method to induce depth in the display, and presented the two directions of motion at separate depths, the search turned out to be parallel. This finding indicates that a discontinuity in motion at a certain depth (all the distractors moved in one direction while the target moved in the opposite direction) can be detected automatically by the visual system.

More explicit evidence of a lack of serial search in conjunctions involving motion was provided by Mcleod, Driver and Crisp (1988) who showed that reaction times did not increase significantly with display size when observers were asked to indicate the absence or presence of a moving X among moving O's and stationary X's. They also replicated this finding with moving 'R' among stationary 'P' and moving 'Q' which, in the absence of motion, is a serial search. This shows that adding the property of motion leads to a clear grouping of the items in the display based on motion. Hence what has been a conjunction search at the level of features ceases to be so when motion is one of the defining properties of the target. It also indicates that motion in the visual field can be detected pre-attentively.

The most popular accounts of capture by motion come from hypotheses regarding behavioural urgency and animacy (Abrams & Christ, 2003; Franconeri & Simons, 2003; Pratt, Radulescu, Guo, & Abrams, 2010). The results in favour of capture by motion are not clear cut. Most of the studies that tested the effects of motion per se did not find capture (Hillstrom & Yantis, 1994; Folk, Remington & Wright, 1994). For example, Hillstrom and Yantis (1994) tested if a motion singleton captured attention. They used search displays where one of the search items possessed a motion attribute while the others did not. When motion reliably predicted target location, search was efficient – as evidenced by a flat search slope. However, when motion was task irrelevant, then reaction times increased as a function of display size. Thus, it is evident that even though motion can reliably be used to guide attention when required, it did not interfere with top-down goals and hence, did not capture attention in a bottom-up manner.

However, the pre-cueing paradigm mostly produced reliable capture as long as the cue and target matched. For example, Folk, Remington and Wright (1994) found that motion captured attention when it was used to cue the location of a forthcoming moving target. They used different types of static and dynamic targets and paired them with a motion cue. A 100% invalid motion pre-cue interfered with the processing of a target defined by motion, but not colour or onset. There were also significant RT benefits when the cue was 100% valid. This shows that motion triggers a contingent involuntary orienting to the location of the cue and hinders performance when the cue is invalid and aids it when it is valid. However, as noted before, there are methodological concerns with the use of pre-cues.

Preliminary evidence in favour of capture by motion was given by Franconeri and Simons (2003), who tested the range of dynamic stimuli that might capture attention. In three experiments, they compared the attention capturing effects of eight types of discontinuities – one static (colour) and seven dynamic (abrupt onset, linear motion, jitter motion, looming motion, receding motion, disocclusion and motion over occlusion). They used displays with figure-8 placeholders and motion started 150 ms before the search display was revealed. They found that all dynamic discontinuities except receding motion capture attention – as evidenced by their respective search slopes. Colour did not capture attention.

They proposed the behavioural urgency hypothesis which claims that attention is captured by events that are behaviourally relevant – i.e., they warrant an urgent response. However, it has been criticised that capture is mediated by the uniqueness of the motion event. Precisely, because motion started 150 ms prior to the beginning of search, the motion event should have been highly salient (for example, see the Unique Event Account – von Mühlenen et al. (2005)). Even though other studies have found evidence supporting capture by looming motion (Franconeri & Simons, 2005; von Mühlenen & Lleras, 2007; Skarratt, Cole & Gellatly, 2009), researchers have found it difficult to replicate attention capture by motion when it did not start just before or during the presentation of the search display (von Mühlenen, etal., 2005).

For example, Abrams and Christ (2003) used displays similar to that used by Franconeri and Simons (2003). Figure-8 placeholders started moving at the beginning of the trial and continued moving even after the search display was revealed by shedding the relevant line segments. They did not find attention capture by motion. Instead, however, they proposed that the onset of motion in a display is salient enough to capture attention. Their display consisted of four figure-8 placeholders, two of which moved and two that did not. After 3200 ms, the search display was revealed by shedding relevant line segments (I will refer to this as display transition).

At display transition, one of the moving placeholders stopped moving while one of the stationary placeholders started moving; the remaining moving item continued moving while the stationary item remained stationary. The target was equally likely to be any of the four items, namely a motion offset, motion onset, continuous motion or static, respectively. They found that motion onset reliably captured attention in spite of the onset of motion being completely irrelevant to the task. Continuous motion and motion offset did not.

In subsequent experiments, they found that motion onset elicited an IOR response and that reaction times were insensitive to an increase in display size when the target was a motion onset item as opposed to a static item. On a same note, using a similar paradigm, they also showed that the onset of receding motion captures attention (Abrams & Christ, 2005). They also found that it is not dependent on changes in luminance associated with the motion (Guo, Abrams, Moscovitch & Pratt, 2010). They also compared the attentional effects of motion onset against that of a new object and found that although there is a definitive RT advantage of an onset of motion, it is not as much as that given by the sudden appearance of a new object (Christ & Abrams, 2008). Indeed, when accompanied by a high energy luminance mask, the attentional benefits afforded by motion onset were completely abolished whereas that afforded by a new object remained.

The evidence accrued in favour of attention capture by the onset of motion is somewhat confusing. There are a number of studies by Abrams and colleagues that argue that the onset of motion captures attention. However, there are instances where the effect goes away- for example, the use of an energy mask. Also, there are certain types of motion onset that capture attention while there are others that do not – for example, looming versus receding motion. One key to solving the confusion come from the study by von Mühlenen et al. (2005).

They found that any feature change captures attention as long as it occurs at a temporal gap when no other event is occurring. This explains why motion captured attention in Franconeri and Simons' (2003) experiments. (It does not, however, resolve why they did not find capture with receding motion.)

Importantly, von Mühlenen et al. did not find capture with motion onset when motion onset started simultaneously with the search display. Even though there are a number of theories to account for the RT patterns observed using the onset of motion (behavioural urgency, animacy etc.), none of them can reliably predict when an onset of motion captures attention and when it does not. Also, the theories do not indicate the possible mechanism underlying attention capture by motion onsets. The present thesis aims to investigate the apparent discrepancies surrounding attention capture by motion and at the same time provide an insight into the possible mechanisms underlying capture.

Chapter 2: Pilot Study – Attention capture with multiple dynamic events.

Introduction

In a serial search model, attention capture can be equated to automatic prioritisation of a particular item in the search. For example, a capture effect by abrupt onset often means that search begins at the location of that particular item. When plotting RTs as a function of display size, this leads to a flat search function for when the target is the onset. This is because search can terminate without examining the other items in the display. One of the key questions of this thesis is how attention is guided to multiple simultaneous events, such as onsets, which are known to capture attention when they occur as a singleton. For example, when two onsets are presented simultaneously, the overall RT benefit for an onset target should be reduced because the probability of the target being the onset that I selected is halved (i.e., within the serial search framework, priority is now shared amongst two items).

It was previously argued that up to four onsets can be prioritized and searched before searching the remainder of the display (Yantis & Johnson, 1990; Yantis & Jones, 1991). In fact, their model assumes that always all onsets are tagged, but then the tags decay over time, allowing only about 3-4 onset items to be searched with priority. Once the tags have decayed, the onset and no-onset items become indistinguishable.[1] According to this model, one would expect a substantial attenuation of the onset effect when the number of onsets is increased. This is simply

[1] Whether all onsets are tagged (and the tags decay), or whether only a limited number of onsets are tagged, will not be addressed in this thesis (see Yantis & Jones, 1991, for an investigation of the tag decay process). For simplicity it is assumed that the number of tags is limited.

because the average number of onsets to be searched before finding the target would linearly increase with each additional onset (i.e., from 1, 1.5, 2, 2.5 items etc. for 1, 2, 3 or 4 onsets).

This same model would predict an attenuation of the capture effect while pitting different types of events against each other. For example, Christ and Abrams(2008) used a visual search display with four types of stimuli: abrupt onset, motion onset, continuous motion, and static stimuli (they called these new object, new motion, old motion and old object, respectively). Stimulus type was irrelevant to the search task. Based on RT differences, they suggested that while abrupt onset and motion onset captured attention, continuous motion did not. Whether these capture effects for abrupt onsets and motion onsets interacted or attenuated each other is not clear from their study, nevertheless, there are certain indicators for such an interaction. For example, in their Experiment 2, they inserted a high energy mask (a blank white screen) of 200 ms between the placeholder display and the search display. This abolished the motion onset effect and substantially attenuated the onset effect. However, in Experiment 3, when the abrupt onset stimulus was removed from the display, the motion onset effect re-emerged in spite of the energy mask. This suggests that capture by abrupt onsets attenuate the motion onset effect. However,it is not clear whether capture by motion onsets in turn attenuate the onset effect.

Two pilot experiments were conducted in order to fully explore the possible interaction between different events that might capture attention. In the first experiment, static, onset and continuous motion stimuli were intermixed in all possible factor combinations. As continuous motion does not capture attention, no attenuation to capture by onsets in conditions where it co-occurs with static or moving stimuli was expected. In the second experiment, continuous motion was replaced with motion onset. Since motion onset is expected to capture attention, an attenuation of capture by both onset and motion onset when they co-occur with each other was expected.

Pilot Experiment 1

Pilot Experiment 1 was designed as an exploratory study to look at the effect of various target distractor combinations on search performance. More specifically, how do continuous motion, abrupt onset and static items presented simultaneously in a display affect prioritization in search. Participants searched for targets U or H among distractors S and E in a display with three items. The display size was fixed at three in order to look at the RT differences as a first step to understand attentional prioritisation. In this and some of the subsequent experiments, RT differences are taken as the primary indicator of capture. The target as well as distractors could be any among abrupt onset, static and motion. This results in six possible distractor combinations, namely, static-static, onset-onset, motion-motion, onset-static, motion-static and onset-motion. In previous studies it has been shown that a continuously moving stimulus does not capture attention (Hillstrom & Yantis, 1994). Hence in the present experiment, it was expected that no costs would occur when onsets are presented simultaneously with continuous motion stimuli. However, in trials with more than one onset, search times may be slower than in trials with no or only one onset.

Method

Participants. A group of ten undergraduate students (3 male, 7 female, mean age 20.1) from the University of Warwick participated in return for course credit. They all had normal or corrected to normal visual acuity. Participants were naïve as to the purpose of the study.

Apparatus and Stimuli. The stimuli consisted of a fixation cross, figure-8 placeholders, and letters, presented in grey drawn on a black background. The fixation cross had a size of 0.6° of visual angle and was presented at the centre of the screen. The figure-8 placeholders and letters subtended 1° × 2° and were made of seven line segments (length 1.0°, thickness 0.13°). The letters were “H,” “U,” “S,” and “E” and were made by removing the corresponding line segments from the figure-8 s. The stimuli were placed on the three imaginary corners of a randomly oriented equilateral triangle centred on fixation (the fixation–letter distance was 12.5°). Letters in the search display were stationary or moved on a circular path (radius = 1.3°) at a constant speed of 8.7°/s, at which speed a full rotation took 960 ms (see Figure 2.1). The moving direction was varied randomly between clockwise and anticlockwise.

Procedure and Design. A trial started with the presentation of a placeholder display that consisted of a fixation cross and two figure-8 placeholders. After 960 ms, the placeholder display was replaced by the search display, which always contained three letters. When present, the static and moving letters were revealed by deleting the irrelevant line segments from the corresponding placeholders, whereas the onset letter appeared at the previously unoccupied location. The target was equally likely to be an abrupt onset, a moving or a stationary item. Distractor combination was also systematically varied: static-static, moving-moving, onset-onset, static-moving, static-onset, moving-onset, giving a total of six possible distractor combinations.

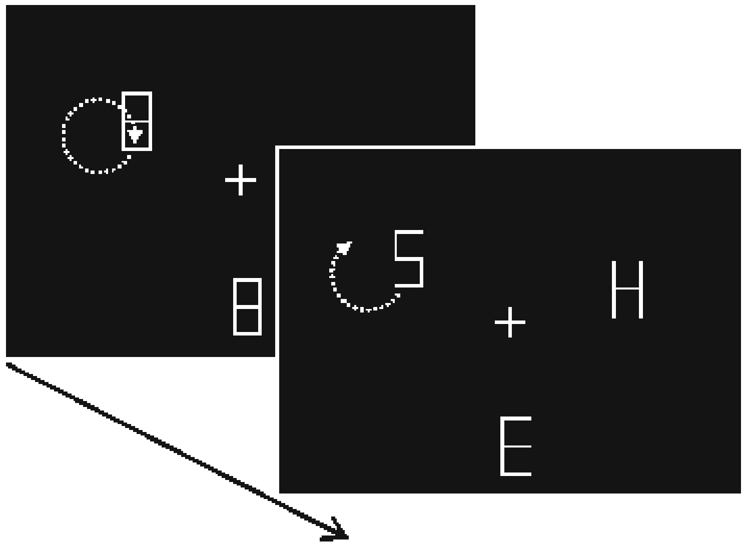

Figure 2.1. Example display showing an onset target "H" and a moving distractor "S" and a static distractor "E" for Pilot Experiment 1.

Participants were asked to look for "H" and "U" targets among "S" and "E" distractors and to respond with the arrow keys. Half of the participants used the left arrow for "H" and the right arrow for "U," and vice versa for the other half. They were instructed to respond to the target as fast as they could whilst trying not to make more than 5% errors. The search display stayed on until the participant responded or until 10 s had elapsed. In the case of wrong responses, immediate feedback reading "error" was given on the screen, and participants had to press the space bar to continue the experiment. The next trial started after an interval of 1 s. Each participant completed 20 practice trials followed by 540 experimental trials. The experimental trials were divided into 10 blocks of 54 trials each, with short breaks between blocks. There were 30 trials in each target type - distractor combination.

The experiment systematically varied three factors: target identity (“H” or “U”), target type (static, onset, or moving), and distractor combination (onset-onset, motion-motion, static-static, onset-motion, onset-static and static-motion). All possible factor combinations were presented in a random order. For the analysis, target identity was not further considered.

Results

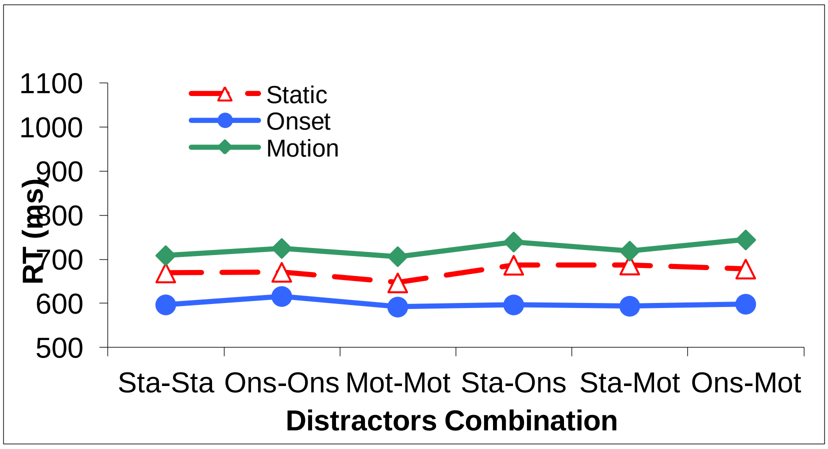

Figure 2.2. Mean correct RT in Pilot Experiment 1 as a function of distractor combination, with separate lines for static, onset and motion target types.

RTs. Mean correct RTs were calculated separately for each participant and factor combination, excluding outlier trials with RTs smaller than 200 ms or larger than 2,000 ms (1.2%). Figure 2.2 shows the averaged RTs as a function of distractor combination, with separate lines for each target type.

The RTs were submitted to a 3×6 repeated measures ANOVA with the factors target type (static, onset, or moving) and distractor combination (static-static, onset-onset, motion-motion, static-onset, static-motion and onset-motion). There was a significant main effect of target type, $F(2, 18) = 56.54$, $p < .001$: Post-hoc LSD tests revealed that onset targets were found faster than static targets, which in turn were found faster than moving targets (599, 674 and 724 ms respectively). Neither the effect of distractor combination ($F = 1.5$, $p = 0.19$) nor its interaction with target type ($F < 1$) were significant.

Table 2.1.

Mean Percentage Error in Pilot Experiments 1 and 2

	Target Type		
Distractor Combination	Static	Onset	Moving
Pilot Experiment 1			
Static-Static	2.5	5.0	5.0
Onset-Onset	6.5	2.0	4.5
Motion-Motion	6.0	3.5	3.5
Static-Onset	5.3	3.8	4.0
Static-Motion	4.5	5.5	6.5
Onset-Motion	8.0	4.8	5.5
Pilot Experiment 2			
Static-Static	5.0	4.6	3.8
Onset-Onset	7.1	2.1	4.6
Motion-Motion	6.7	2.5	3.8
Static-Onset	6.7	4.2	6.0
Static-Motion	6.0	4.0	5.8
Onset- Motion	4.6	4.6	5.6

Errors. Mean percentage errors were calculated separately for each participant and factor combination (see Table 2.1). The 3 × 6 repeated measures ANOVA did not show any significant differences as error rates were comparable across conditions (5.4 vs. 4.1 and 4.8%).

Discussion

The results of Pilot Experiment 1 show that the RT to find an onset target is overall faster than the RT to find a static target. They also show that it takes longer to find a continuously moving target than to find a stationary target. However, distractor combination had no significant effect on search times.

These results suggest that the presence of a moving item in the display did not interfere with attention capture by abrupt onsets. However, surprisingly, the presence of more (one or two) onset distractor did also not reduce the capture effect by abrupt onsets. This is surprising because one would expect some costs when there are multiple onsets in the display. Even though the cost of having multiple abrupt onsets have not been quantified, Yantis and Johnson (1990) showed that up to four onsets are prioritised and searched before searching through the remaining items in the display. In their study RTs increased as the number of onsets in a display increased. However, in their study, the total display size also increased with an increase in the number of onsets as they always had an equal number of onset and static items.

Another possible explanation for the lack of increase in RT with increasing number of onsets is the relatively small display size. In the present study, the display size was always three. It is possible that all three locations were selected simultaneously for processing and any difference in RT is attributed to perceptual differences between the three stimulus types and not owing to attentional prioritization. A larger display size would help to prevent such a confound as it has been shown that only up to 4 locations can be selected simultaneously with high precision (Franconeri, Alvarez & Enns, 2007). This possibility will be further explored in Chapter 6 where the number items in the display is eight and the number of onsets is systematically varied from 0 to 8 items.

Pilot Experiment 2

Pilot Experiment 2 further explored the possible attenuation of capture in multi-element displays. It was supposed that attenuation might occur in the simultaneous presence of more than one type of stimulus, when both of them capture attention. It has been shown that even though continuous motion does not capture attention, the onset of motion does (Abrams & Christ, 2003; Franconeri & Simons, 2005). Hence in the second pilot experiment, continuous motion was replaced with motion onset (that is, the stimulus started moving only during display transition, where the placeholders were replaced by letters).

Method

Participants. Fourteen undergraduate students (6 male, 8 female, mean age 19.6) from the University of Warwick participated in return for course credit. They all had normal or corrected to normal vision.

Apparatus, Stimuli, Procedure and Design. The apparatus and stimuli were the same as in Pilot Experiment 1, except that now motion started simultaneously with the figure-8 placeholders changing to letters. All aspects of the procedure and design were identical to that of the Pilot Experiment 1.

Results

RTs. Figure 2.3 shows the averaged RTs as a function of distractor combination, with separate lines for each target type. RTs were submitted to a 3 × 6 repeated measures ANOVA with the factors target type (static, onset, or motion onset) and distractor combination (static-static, onset-onset, motion-motion, static-onset, static-motion and onset-motion).

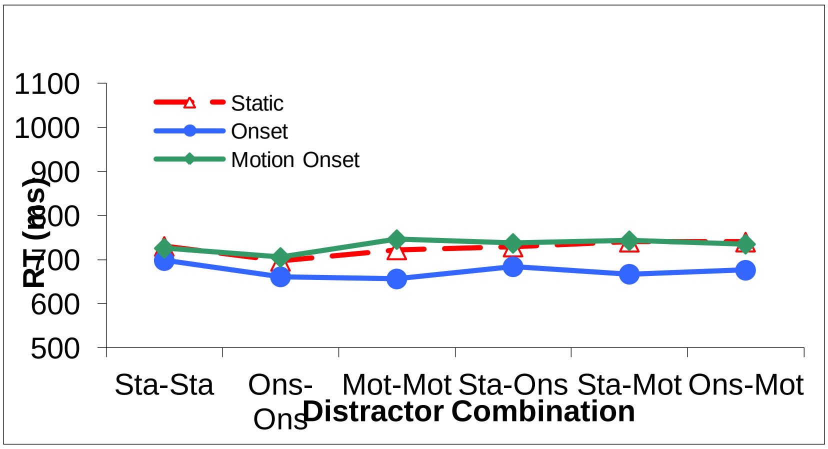

Figure 2.3. Mean correct RT in Pilot Experiment 2 as a function of distractor combination, with separate lines for static, onset and motion onset targets.

There was a significant main effect of target type, $F(2, 26) = 21.83$, $p < .001$: Post-hoc LSD tests revealed that onset targets were found significantly faster than static targets, but there was no significant difference in RTs between static and moving target types (674, 727 and 732 ms, respectively). There was also a significant main effect of distractor combination, $F(5, 65) = 3.9$, $p < .01$: LSD tests revealed that this is due to the RTs being on average 29 ms slower in the condition where both distractors are static, than in the other five conditions. The two-way interaction between target type and distractor combination was not significant $F(10, 130) = 1.36$, ns.

Errors. Mean percentage errors were calculated separately for each participant and factor combination (see Table 2.1). The 3 × 6 repeated measures ANOVA revealed only a marginally significant main effect for Target type, $F(2, 22) = 2.87$, $p = .08$, due to slightly increased error rate with static targets, compared to onset and motion onset targets (6.0 vs. 3.7 and 4.9%).

Discussion

The results of Pilot Experiment 2 showed that search was overall faster when the target had an abrupt onset as compared to when it was stationary or when it started moving. This suggests that an abrupt onset, but not a motion onset captured attention. This is inconsistent with findings in the literature (see, Abrams & Christ, 2003, 2005; Christ & Abrams, 2008; Christ et al., 2008; Franconeri & Simons, 2003) where capture was observed with motion onset. One key to resolving this issue might come from the Unique Event Account (UEA) of attention capture, proposed by von Mühlenen, Rempel and Enns (2005). According to the UEA, capture by most events is modulated by their temporal uniqueness. That is, motion onset, for example, would capture attention when motion starts just before or after the placeholder display changes to the search display (display transition). However, when motion onset begins at display transition, capture does not occur as the motion onset signal is masked by other simultaneous changes to the display (like the figure-8s changing to letters). In Franconeri and Simons' study, motion began always 150 ms before display transition while in the present experiment it began during display transition. Thus, it is possible that the absence of capture by motion onset in the present study is due to motion onset being a non-unique event.

The absence of capture by motion onset might also explain why there is no attenuation of capture effect for abrupt onset targets when the distractors are heterogeneous. Moreover there is no attenuation resulting from the presence of multiple onset distractors, replicating the results of Pilot Experiment 1.

The present two pilot experiments leave open two important questions: (1) Why is there no capture by motion onset in the present experiment in spite of many replications of this effect by Abrams and Colleagues (Abrams & Christ, 2003, 2005; Christ & Abrams, 2008; Christ et al., 2008)? (2) Why is there no significant attenuation to capture by abrupt onsets when multiple onsets are presented? These two questions form the basis of the experimental work done in the course of my PhD and they will be both addressed in the following empirical chapters.

Overview of the Empirical Chapters

In the following sections I present four empirical chapters examining attention capture by motion onsets and abrupt onsets. The first three chapters are concerned with explaining the nature of attention capture by motion onsets, while the last looks at the effect of number of onsets that are prioritised in search. The first chapter reports two experiments that test the role of motion refresh rate in attention capture. The results suggest that capture is strongly mediated by motion refresh rate. The findings also contest Abrams and colleagues findings, which seem to strongly depend on their use of low refresh rate (i.e., jerky) motion.

The second chapter further explores the reasons for capture by jerky motion. Five experiments suggest that low level changes play a strong role in attention capture and they suggest a possible single mechanism that accounts for attention capture by abrupt onsets and by motion onsets (as shown by Abrams and colleagues). The third chapter reports three experiments that show a new aspect of motion change that captures attention – namely a change in the direction of motion.

Finally, the fourth chapter explores the attention capture by multiple onsets. The overall display size was fixed and the number of onsets was systematically varied. The results suggest that only a single onset is automatically prioritised when the onset status is irrelevant to the search task. However, when the onset status becomes task relevant, selective processing of more than one item can be achieved.

Overall, the results of all four empirical chapters support a more unitary mechanism of capture, which is sensitive to low level perceptual factors and which speaks for a purely stimulus driven account of capture.

Chapter 3: Motion onset does not capture attention when subsequent motion is “smooth"

Introduction

Motion in the visual field carries important information that is critical for an observer to successfully deal with everyday events (Gibson, 1950), such as a suddenly approaching car or a waving hand. The human visual system is known to have specialized motion processing capabilities, and one might suspect that motion automatically attracts attention, in order to prioritize the processing of information associated with the motion. However, research in the laboratory has, in general, not supported this idea (e.g., Hillstrom & Yantis, 1994; Yantis & Egeth, 1999; for reviews, see Rauschenberger, 2003; Theeuwes, 2010). For example, Hillstrom and Yantis used a visual search task and showed that a moving stimulus (or a stimulus containing a moving texture) was not easier to find than a stationary stimulus unless the motion was predictive of the target's location or the motion resulted in the appearance of a new object.

However, these ideas have been contested by a number of studies showing, for example, that motion can have an effect on attention under certain conditions. For example, capture occurred when motion was used as a cue for a motion-defined target, but not for a target that was defined in another dimension, such as color or abrupt onset (Folk, Remington, & Wright, 1994). Others have suggested that attention capture occurs only with certain types of motion, such as linear, oscillating, and looming motion (Franconeri & Simons, 2003; Skarratt, Cole, & Gellatly, 2009; von Mühlenen & Lleras, 2007). Moreover, von Mühlenen, Rempel, and Enns (2005) argued that capture does not solely depend on motion type, but also on the timing of motion (e.g., motion starts 150 ms before search begins).

Finally, Abrams and Christ (2003) supported Hillstrom and Yantis's (1994) finding that motion per se does not capture attention, but instead that the onset of motion is what captures attention. They used a visual search task with four stimuli, each having a task-irrelevant motion attribute: continuous motion, motion onset, motion offset, and static. They showed that although a continuously moving target was not easier to find than a static target, a motion-onset target was, supporting their motion-onset account. In two other studies, they replicated this benefit for a motion onset when comparing it with abrupt onsets (Christ & Abrams, 2008) and also when testing older people (Christ, Castel, & Abrams, 2008). The reasoning behind the motion-onset account is that continuous motion, as such, is far too common in our natural environment to be informative of behaviourally urgent events. However, the onset of motion can be important for the categorization of objects as animate or inanimate—which, in evolutionary terms, might be vital for the detection of prey and predators (e.g., Scholl & Tremoulet, 2000).

von Mühlenen et al. (2005) also found that the onset of motion (and not motion per se) captures attention, but only if the onset is temporally unique. According to their unique-event account, any sudden change is capable of capturing attention as long as it occurs at a time when nothing else is happening in the visual field. While the motion-onset account assumes that motion onset enjoys a special status in attention capture (like abrupt onsets), the unique-event account assumes that motion onset is like any other sudden change (i.e., colour, luminance, or shape changes), which will capture attention only when it is temporally unique.

Contradictory to von Mühlenen et al.'s (2005) findings, Abrams and Christ (2003) found capture for motion onset when it was not unique—for example, when it co-occurred with display transition, where figure-8 placeholders changed to letters. There were a number of notable differences between the two studies: First, in von Mühlenen et al.'s study, motion attributes were varied across different experiments, whereas in Abrams and Christ's (2003) study, motion attributes co-occurred within the same trial. Second, von Mühlenen et al. used slope differences (RT as a function of display size) as a measure for attentional capture, whereas Abrams and Christ (2003) primarily used differences in the RTs. Finally (and I believe most critically), von Mühlenen et al. used relatively smooth motion (85 Hz), whereas Abrams and Christ (2003) used rather jerky motion (15 Hz). Perhaps the form of crude motion used by Abrams and Christ (2003, as well as by in Christ & Abrams, 2008, and Christ et al., 2008) produced abrupt changes that captured attention. If this were the case, capture would occur only with jerky, but not with smooth, motion.

In order to test this hypothesis, an experiment that could replicate Abrams and Christ's (2003) finding while also manipulating the motion refresh rate was designed. In contrast to von Mühlenen et al. (2005), it was decided not to vary display size in this study, in order to prevent the number of trials from escalating, and because it was consider it to be less critical for the purpose of our study. Consequently, absolute RT differences, which are generally considered to be less reliable than slope differences (e.g., Simons, 2000), were used as an indicator for attentional capture. However, this seemed a justifiable compromise, given that our primary concern was to see whether the RT difference in Abrams and Christ's studies—irrespective of whether it indicated attention capture—critically depended on the jerky motion that they used.

Experiment 3

Experiment 3 used the same basic methodology as Christ and Abrams (2008). The trial sequence showed two figure-8 placeholders followed by three letter stimuli (one static, one onset, and one moving stimulus).[2] The moving stimulus was refreshed at 100, 33, 17, or 8 Hz, leaving intervals of 10, 30, 60, or 120 ms, respectively, between consecutive frames. In Experiment 3, the moving stimulus started moving at the display transition (from figure-8 to letters). It was predicted that the RT difference between the static and moving target types would critically depend on the motion refresh rate.

Method

Participants. A group of 14 undergraduates (5 male, 9 female; mean age 19.7 years) from the University of Warwick participated in return for course credit. All of them reported normal or corrected-to-normal vision and were naïve to the purpose of the experiment.

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[2] Christ and Abrams (2008) used a fourth stimulus type, termed a "new moving object," in which the target was a moving abrupt-onset stimulus. This stimulus type was not included here because their results in this condition did not differ from the static abrupt-onset condition.

Apparatus and Stimuli. The participants were seated in a dimly lit, sound-attenuated room in front of a 19-in. CRT monitor at a distance of approximately 57 cm. The monitor was driven at 100 Hz at a resolution of 1024 × 786 pixels. The experiment was controlled by a PC-compatible computer using custom-written software. Participants' responses were recorded using the left and right arrow keys on a standard keyboard.

The stimuli consisted of a fixation cross, figure-8 placeholders, and letters, presented in grey drawn on a black background. The fixation cross had a size of 0.6° of visual angle and was presented at the centre of the screen. The figure-8 placeholders and letters subtended 1 × 2° and were made of seven line segments (length 1.0°, thickness 0.13°). The letters were "H," "U," "S," and "E" and were made by removing the corresponding line segments from the figure-8s. The stimuli were placed on the three imaginary corners of a randomly oriented equilateral triangle centred on fixation (the fixation–letter distance was 12.5°).

Letters in the search display were stationary or moved on a circular path (radius = 1.3°) at a constant speed of 8.7°/s, at which speed a full rotation took 960 ms (see Fig. 3.1). The moving direction was varied randomly between clockwise and anticlockwise. The refresh rate of the moving stimulus was systematically varied among 100, 33, 17, and 8 Hz. For example, a 100-Hz stimulus was updated every 10 ms (displaced by 0.09º), producing the impression of smooth motion, whereas an 8-Hz stimulus was updated every 120 ms (displaced by 1.05º), producing the impression of jerky motion. This meant that motion speed was held constant while motion quality was systematically varied.

Procedure and Design. A trial started with the presentation of a placeholder display that consisted of a fixation cross and two figure-8 placeholders. After 960 ms, the placeholder display was followed by the search display, which always contained three letters. The static and moving letters were revealed by deleting the irrelevant line segments from the corresponding placeholders, whereas the onset letter appeared at the previously unoccupied location. Stimulus movement began when the placeholders changed to letters (see Figure 3.1).

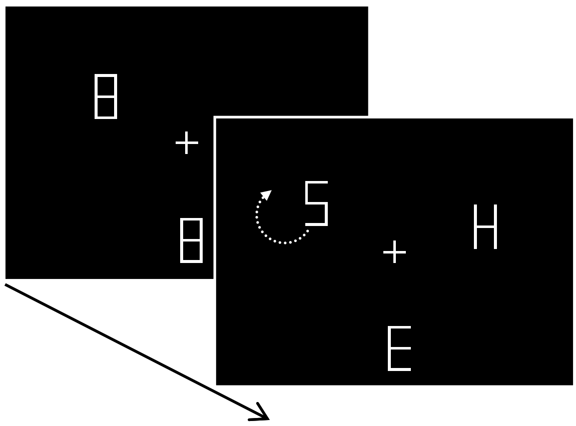

Figure 3.1. Example display from Experiment 3. Stimulus movement began when the placeholders changed to the letter stimuli

Participants were asked to look for “H” and “U” targets among “S” and “E” distractors and to respond with the arrow keys. Half of the participants used the left arrow for “H” and the right arrow for “U,” and vice versa for the other half. They were instructed to respond to the target as fast as they could whilst trying not to make more than 5% errors. The search display stayed on until the participant responded or until 10 s had elapsed. In the case of wrong responses, immediate feedback reading “error” was given on the screen, and participants had to press the space bar to continue the experiment. Otherwise, the next trial started after an interval of 1 s. Each participant completed 20 practice trials followed by 480 experimental trials. The experimental trials were divided into 10 blocks of 48 trials each, with short breaks between blocks.

The experiment systematically varied three factors: target identity (“H” or “U”), target type (static, onset, or moving), and motion refresh rate (100, 33, 17, or 8 Hz). All possible factor combinations were presented in a random order. For the analysis, target identity was not considered further.

Results

RTs. Mean correct RTs were calculated separately for each participant and factor combination, excluding outlier trials with RTs smaller than 200 ms or larger than 2,000 ms (1.6% of all trials). Figure 3.2 shows the averaged RTs as a function of motion refresh rate, with separate lines for each target type. As can be seen, a moving target was found as quickly as an onset target or as slowly as a static target, depending on the motion refresh rate.

Individual mean RTs were submitted to a 3 × 4 repeated measures ANOVA with the factors target type (static, onset, or moving) and motion refresh rate (100, 33, 17, or 8 Hz). There was a significant main effect of target type, $F(2, 26) = 23.16$, $p < .001$: Post-hoc LSD tests revealed that onset targets were found significantly faster than moving targets, which in turn were found significantly faster than static targets (756, 813, and 862 ms, respectively). There was also a significant main effect for motion refresh rate, $F(3, 39) = 5.64$, $p < .01$: LSD tests revealed that RTs in the 8-Hz condition were significantly slower (on average, 29 ms) than RTs in the other three conditions. The two-way interaction was also significant, $F(6, 78) = 3.13$, $p = .01$.

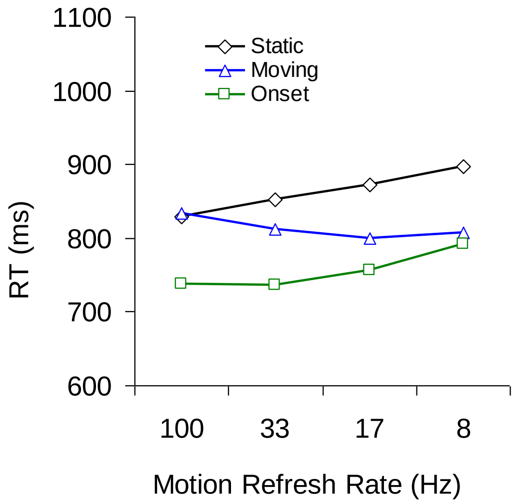

Figure 3.2. Mean correct RTs as a function of motion refresh rate in Experiment 3, with separate lines for each target type.

To further explore the two-way interaction, three separate 2 × 4 split-up ANOVAs were conducted comparing each possible pair of target type levels. A significant target type × motion refresh rate interaction was found in the static–moving pair, $F(3, 39) = 4.9$, $p < .01$, and in the onset–moving pair, $F(3, 39) = 3.85$, $p = .01$, but not in the static–onset pair ($F < 1$). As can be seen in Figure 3.2, the static line appears parallel to the onset line, but not to the moving line. Separate Bonferroni adjusted t tests revealed that moving targets were found significantly faster than static targets at 8 Hz and 17 Hz, but significantly slower than onset targets at 33 Hz and 100 Hz (all $p < .01$). To summarize, a rather “smoothly” (100 or 33 Hz) moving target was not found any faster than a static target, whereas a rather “jerkily” (17 or 8 Hz) moving target was found as quickly as an onset target.

Table 3.1.

Mean percentage errors in Experiments 3 and 4

	Target Type		
Motion Refresh Rate	Static	Onset	Moving
Experiment 3			
100 Hz	5.7	2.7	5.7
33 Hz	5.5	2.5	4.5
17 Hz	6.3	3.8	3.8
8 Hz	4.5	2.7	5.4
Experiment 4			
100 Hz	4.4	4.8	5.0
33 Hz	6.9	3.3	5.0
17 Hz	3.3	3.1	3.1
8 Hz	3.8	2.9	5.0

Errors. Mean percentage errors (see Table 3.1) were calculated separately for each participant and variable combination. A 3 × 4 ANOVA with the factors target type and motion refresh rate revealed a significant main effect of target type, $F(2, 26) = 5.68$, $p < .01$, due to fewer errors in the onset condition than in the static and moving conditions (2.9% vs. 5.5% and 4.8%, respectively). While the two-way interaction was not significant, $F(6, 78) = 1.13$, n. s., errors overall showed a very similar pattern to the RTs, suggesting that the RTs are not confounded by speed–accuracy trade-offs.

Discussion

The results showed that a moving target is easier to find than a static target only when the motion refresh rate is low. This perfectly corresponds with previous findings: On the one hand, the results in the 100-Hz condition replicated the pattern found by von Mühlenen et al. (2005) with display size three (829, 833, and 738 ms vs. 618, 615, and 576 ms for static, moving, and onset targets, respectively), showing no evidence for capture by motion onsets. This represents, in our view, the key finding of Experiment 3, because it invalidates Abrams and Christ's (2003) account, according to which a motion onset should always capture attention.

The absence of capture denies motion onset a special role in attention capture, leaving motion onset on a par with any other feature change. However, this absence can easily be explained within the theoretical framework provided by von Mühlenen et al.'s (2005) unique-event account, according to which motion onset should not capture attention when it occurs simultaneously with a display transition (i.e., when it is not temporally unique).

On the other hand, the RTs in the 17-Hz condition for static, moving, and onset targets replicated Christ and Abrams's (2008) RTs (872, 800, and 756 vs. 766, 690, and 614 ms, respectively).[3] It is also in line with other similar findings by Abrams and colleagues (Abrams & Christ, 2003; Christ et al., 2008), for which they

[3] Our participants were somewhat slower and made more errors than Christ and Abrams's (2008) participants, but this is most likely due to differences in the homogeneity of the distractors (i.e., in a given trial, we used different distractor letters, whereas they used identical letters).

used 15-Hz motion.[4] Whereas Abrams and Christ interpreted their finding as evidence for capture by motion onset, the present study suggests that this effect was induced by motion jerkiness.

One possible effect of motion jerkiness could be that the relatively large displacement of the moving stimulus produces a kind of transient flicker that captures attention (e.g., Ludwig, Ranson, & Gilchrist, 2008; Spalek, Kawahara, & Di Lollo, 2009). This and other explanations will be taken up again in the General Discussion. To sum up, the present study reconciles these apparently conflicting results by showing that the RT benefit for motion-onset targets depends on the motion refresh rate.

Figure 3.2 might suggest that the interaction between target type and motion refresh rate is driven by an RT increase in the static condition (68 ms) rather than by a decrease in the motion condition (-26 ms), as would be expected if motion onset captures attention. However, this could be due to an overall main effect of motion refresh rate that is superimposed on the interaction (e.g., due to the increased perceptual noise/flicker at lower refresh rates).

An indication of such an overlay effect comes from the fact that RTs in the onset condition showed an increase (53 ms) similar to that of RTs in the static condition (this was also true for Experiment 4). Moreover, this main effect was

[4] In one of their studies (Abrams & Christ, 2005), they used smooth, 60-Hz motion in a cueing paradigm. They showed that only the onset of irrelevant motion reduced the inhibition-of-return effect. They interpreted this finding as further evidence for their motion-onset account. However, since the motion onset occurred around 400 ms before the target appeared, this finding is also in line with the unique-event account.

mostly due to the 8-Hz condition (overall 30-ms slower RTs as compared to the other three conditions), where motion jerkiness might have been particularly disruptive.

Experiment 4

In Experiment 4, motion onset was replaced with continuous motion, in which the stimulus started moving at the beginning of the trial and continued to move throughout the trial (see Figure 3.3). The aim was to test whether motion refresh rate had the same attentional effect when the motion-onset signal was absent. Finding the same kind of interaction as in Experiment 3 would indicate that attention is altered by jerky motion per se, whereas the absence of such an interaction would indicate that attention is altered by jerky motion only in combination with motion onset. In other words, Experiment 4 tested whether jerky motion affects the perception of motion per se (e.g., by adding noise) or instead affects the onset of motion (e.g., by boosting or delaying the perceived onset of motion).

Method

Participants. A group of 12 students from the University of Warwick (4 male, 6 female; mean age, 21.3 years) participated in return for £5. All reported normal or corrected-to-normal vision and were naïve to the purpose of the experiment. None had participated in Experiment 3.

Apparatus, Stimuli, Procedure, and Design. The apparatus, stimuli, procedure, and design were the same as in Experiment 1, except that the motion started at the beginning of the placeholder display (see Figure 3.2).

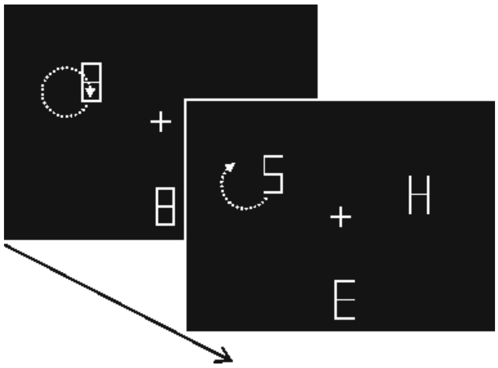

Figure 3.3. Example display from Experiment 4, with continuous motion

Results

RTs. Mean correct RTs, excluding outliers (1.3%), are presented in Figure 3.4. A 3 × 4 ANOVA with the factors target type (static, onset, or moving) and motion refresh rate (100, 33, 17, or 8 Hz) revealed a significant effect for target type, $F(2, 22) = 52.76$, $p < .001$: LSD tests revealed that moving targets were found 75 ms slower than static targets, which in turn were found 103 ms slower than onset targets (all ps < .001). There was also a significant main effect of motion refresh rate, $F(3, 33) = 25.99$, $p < .001$: LSD tests revealed that the 8-Hz condition was 35 ms slower than the 17-Hz condition, which in turn was on average 25 ms slower than the 33 Hz and 100-Hz conditions (all ps < .05, except for the difference between the 33 Hz and 100-Hz conditions: $p = .6 1$). Critically, the two-way interaction was not significant, $F < 1$.

Errors. Mean percentage errors are presented in Table 3.1. A 3 × 4 ANOVA with the factors target type and motion refresh rate revealed no significant effects (all *p*s > .1), indicating that the RT results were not confounded by speed–accuracy trade-offs.

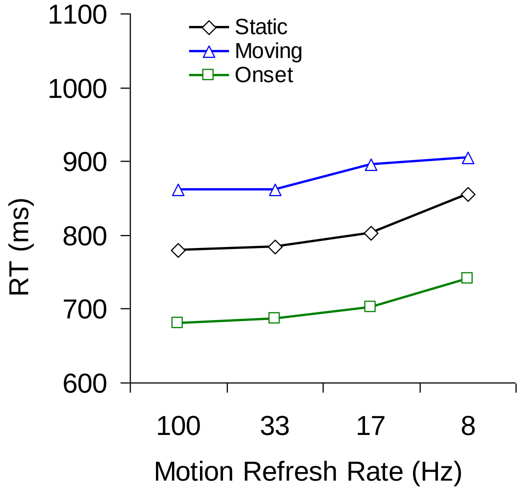

Figure 3.4. Mean correct RTs as a function of motion refresh rate in Experiment 4, with separate lines for each target type

Discussion

Experiment 4 did not show an RT benefit for continuously moving targets, with either smooth or jerky motion. That is, task-irrelevant continuous motion can easily be ignored, irrespective of whether the motion is jerky or not. This result is also consistent with previous findings (Abrams & Christ, 2003; Hillstrom & Yantis, 1994; von Mühlenen et al., 2005) and suggests that jerkiness interferes only with the onset of motion (Experiment 3), not with motion per se (Experiment 4).

Finding a target that was continuously moving actually took longer than finding a stationary target. This somewhat unexpected RT cost is consistent with previous findings. For example, Abrams and Christ (2003) found a similar disadvantage of around 20 ms—which was, however, not statistically significant. Likewise, von Mühlenen et al. (2005) reported a pilot experiment in which search efficiency was impaired when the target was continuously moving. This could be explained by visual degradation of the continuously moving stimulus, either because the visual quality was reduced (e.g., retinal smearing, reduced luminance contrast) or because the cross-referencing of shape features becomes less reliable (for a similar account, see von Mühlenen & Müller, 2000).

General Discussion

The results from the present study can be summarized as follows: When motion is smooth, neither the onset of motion nor continuous motion captures attention. However, when motion is jerky, the onset of motion (but not continuous motion) appears to capture attention. It was argued that the first finding fits with von Mühlenen et al.'s (2005) unique-event account, but not with Abrams and Christ's (2003) motion-onset account. The second finding still needs further explanation. In the discussion of Experiment 3, it was suggested that the transient flicker that accompanies jerky motion might capture attention. However, Experiment 4 ruled out this possibility, by showing that jerkiness did not capture attention when motion was continuous. This suggests that jerkiness affects only the onset of motion. Maybe the temporal delay between two frames turns the moving stimulus into a new object (see

Yantis & Gibson, 1994). However, our moving stimulus—despite its jerkiness—always had an inter stimulus interval of 0 ms, producing a strong impression of second-order motion (i.e., of a single object moving from locations A to B).

Other explanations could be that jerkiness boosts the motion-onset signal, making it strong enough to capture attention, or it delays the perceived onset of motion, turning it into a temporally unique event that captures attention. A possible reason for the perceived delay could be that the very first displacement of the moving stimulus goes unnoticed because of interference from the other changes co-occurring in the display (i.e., the onset and segment removals). Therefore, only the second displacement is noticed, which becomes the perceived onset of motion. More empirical work is required to better understand the nature of this interaction between motion onset and jerkiness.

According to Abrams and Christ (2006), attention capture is not caused by lower-level changes in luminance-defined contours, but instead by higher-level changes in the perceived location of the object. The present study has clearly demonstrated that such a change in the perceived location is not sufficient for attention capture, because capture did not occur with smooth motion, despite the evident change in the perceived location of the object. Thus, the present study allows for a new interpretation of Abrams and Christ's (2003) findings, where lower-level changes play an important role in attentional prioritization. This is also in line with the broader view that attention capture has a strong bottom-up component that is primarily saliency driven (e.g., Theeuwes, 2010). It remains an open question whether the temporal uniqueness of an event, as described by von Mühlenen et al.'s

(2005) account, leads to an increase in the saliency of that event or whether it leads to an increase in the priority of that event at a later processing stage. Nevertheless, the unique-event account provides a useful framework that can account for a wide range of findings.

Chapter 4: The role of motion, flicker and abrupt displacement in attention capture

Introduction

The debate regarding the ability of motion to capture attention is more than a decade old. While most of the studies seem to conclude that motion per se does not capture attention, the evidence is less conclusive for the onset of motion (Abrams and Christ, 2003; von Mühlenen, Rempel & Enns, 2005; Sunny and von Mühlenen, 2011). For example, Abrams and colleagues (Abrams & Christ, 2003, 2005; Christ & Abrams, 2008, Christ, Castel & Abrams, 2008) showed that an object that started moving (motion onset) was automatically prioritized over an object that remained stationary (static), was continuously moving (continuous motion), or had stopped moving (motion offset). They argued from an evolutionary perspective that the onset of motion is important because it could aid fast and reflexive detection of prey or predators. In their *motion onset account* they argued that capture occurs because of a higher level change in the status of an object from stationary to moving rather than from a low-level change signalling the motion onset (Abrams & Christ, 2006). Further evidence for this comes from Franconeri & Simons (2005), who showed that motion onset captured attention even when the physical onset of motion was not perceived (i.e., it occurred during a saccade).

Contradictory to this position that capture depends on higher-level representations, von Mühlenen et al. (2005) argued that lower-level changes to basic object features are crucial in attention capture. They proposed that any change, including motion onset, captures attention only when it occurs during a period of temporal calm (i.e., when nothing else is happening in the display). According to their *unique event account*, changes that happen simultaneously with display transition (i.e., when the placeholders change to search letters) fail to capture attention because the change becomes masked by the other changes in the display. However, this dependence of capture on the timing of events was not in line with the findings of Abrams and Christ (2003, 2005), who found capture even when motion began during display transition.

Experiment 3 and 4 (2011) offered a resolution for this apparent discrepancy, pointing to the refresh rate of motion as the critical difference between the two studies. Abrams and Christ (2003) used a relatively low refresh rate of 15 Hz leaving the impression of rather jerky motion while von Mühlenen et al. (2005) used a refresh rate of 75 Hz leaving the impression of smooth motion. Experiment 3 and 4 systematically varied motion refresh rate, and showed that the attention capture for motion onsets stimuli only occurred with jerky – but not with smooth motion (see Figure 3.1). Experiment 3 showed that continuous motion could be ignored, even when motion was jerky. Thus jerkiness per se cannot account for capture at lower motion refresh rates. Only the combination of jerky motion and motion onset captures attention.

The absence of capture with smooth motion was in line with von Mühlenen et al.'s (2005) unique-event account, according to which motion onset should not capture attention when it occurs simultaneously with display transition. However the reasons for attention capture by the onset of jerky motion are not fully understood.

The differential effects of smooth and jerky motion could be further understood by looking at the physical differences between the two. All motion generated on a computer monitor consists of deleting an object from one location after a specified period of time and redrawing it at a different location for a period of time. When the duration for which the object is shown at one location is short and/or the distance between two simultaneous locations is small, then the object appears to move rather smoothly to the new location. However, when the duration and/or distance increase, then the stimulus appears more to “jump” to the new location, giving the impression of a 'jerky motion'. Even though in both instances the stimulus is clearly perceived as moving from one location to another, capture could nevertheless be mediated by some specificity of these spatial and temporal factors.

The current chapter presents a series of experiments that will further explore why the onset of jerky, but not smooth motion captures attention. The basic idea is to further break apart motion into its components, and to test whether a certain component is necessary or even sufficient to capture attention.

Experiment 5

When motion is jerky, the relatively large displacement of the moving stimulus produces a stream of abrupt changes, which is perceived as a transient flicker. Maybe motion is not required at all, and this type of flicker simply captures attention. Indeed, Seitz, Nanez, Holloway and Watanabe (2006) showed that training in motion perception lowers the threshold for perceiving flicker, suggesting that these are based on related mechanisms. These studies suggest that the abrupt luminance changes associated with flicker might produce attentional effects and that they might be comparable to those produced by jerky motion.

Other studies looking at the attentional effects of flicker also suggested that the dynamics of visual flicker might be used to guide attention. For example, in a visual search task Spalek, Kawahara, and Di Lollo (2009) showed that a flickering target captured attention (i.e., it "popped out") when it flickered at a different frequency than the distractors. This occurred irrespective of the specific frequency of the targets and the distractors (4, 10, 20 Hz), leading to the conclusion that flicker is a primitive visual feature. Additionally, in a contrast discrimination task, Ludwig, Ranson, and Gilchrist (2008) asked participants to fixate a target that had a different contrast in comparison to the distractors. They found that a flicker distractor was particularly disruptive to performance as compared to a motion onset, an abrupt onset or an abrupt offset distractor.

Experiment 5 examines whether the onset of flicker in a non-moving stimulus has the same effect on attention as the onset of jerky motion. If abrupt luminance change is the critical component that captures attention in jerky motion, then a flickering object should also be automatically prioritised in search. Flicker frequency was varied at rates comparable to the motion refresh rates used Experiments 3 and 4.

Method

Participants. Twelve students from the University of Warwick (2 male, 10 female, mean age 19.62 years) participated in return for course credit. Participants were drawn from the same pool for the other experiments in this chapter too. All reported normal or corrected to normal visual acuity and were naïve to the purpose of the experiment.

Apparatus and Stimuli. The experiment was controlled using custom written software, by an IBM-PC compatible computer. Stimuli were presented on a 19" CRT monitor driven at 100 Hz at a resolution of 1024 x 768 pixels. The participants were seated in a dimly lit sound attenuated cubicle, at a distance of 57 cm from the monitor. Participants' responses were recorded using left and right arrow keys on a standard keyboard.

Stimuli consisted of a fixation cross (0.6°), figure-8 placeholders, and letters (both 1° x 2°), presented in grey drawn on black background. The letters were 'H', 'U', 'S' and 'E' and were made by removing the corresponding line segments from a figure-8 placeholder. Stimuli were placed on the three imaginary corners of an equilateral triangle with a randomly varying orientation, centred on fixation (fixation-letter distance was 12.5°). The static and flicker letters were revealed by deleting the irrelevant line segments from the corresponding placeholders, whereas the onset letter appeared at the previously unoccupied corner of the triangle (see Figure 4.2). Flicker at four different frequencies (100, 33, 17 and 8 Hz) were used. At all the frequencies, the stimulus was displayed for 20 ms, and then erased for 0, 10, 40 or 100 ms corresponding to 100, 33, 17 or 8 Hz respectively.

Procedure and Design. A trial started with the presentation of a placeholder display for 960 ms that consisted of a fixation cross and two figure-8 placeholders. This was followed by the search display containing three letters. The search display remained until the participant responded or 10 seconds had elapsed. Participants were asked to look for the target letter 'H' or 'U' among 'S' and 'E' distractors and to respond with the arrow keys. Half of the participants used the left arrow for H and right arrow for U, and vice versa for the other half. They were instructed to respond to the target as fast as they could while keeping the error rate to a minimum (not more than 5%). Error responses were followed by an immediate visual feedback and the prompt to press the space bar to continue. The next trial, started automatically after an interval of 1 second. Each participant completed 20 practice trials followed by 480 experimental trials. The experimental trials were divided into 10 blocks of 48 trials each, with short breaks between blocks.

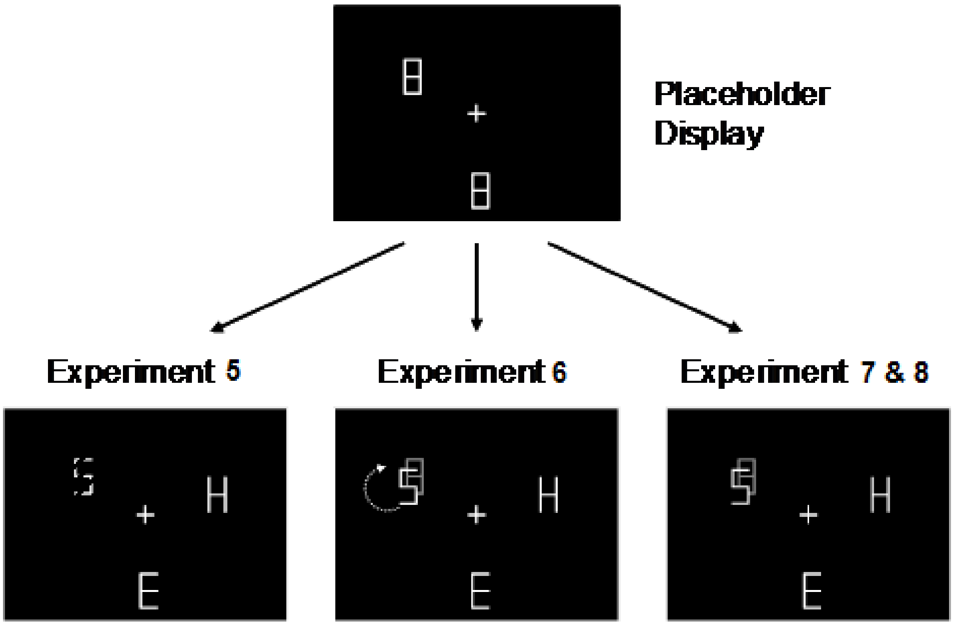

Figure 4.1. Example display for Experiment 5-8. Stimulus flicker (indicated by cross hatch) in Experiment 5 or stimulus displacement in Experiment 6-8 began at display transition when the placeholders changed to letters. The size of the (initial) displacement was systematically varied from 0.09 to 1.05° visual angle. Smooth motion in Experiment 6 is indicated by curved arrow. Gray placeholders in the search displays (Experiment 6, 7 & 8) indicate the displacement and were not visible.

The experiment systematically varied three factors: target identity (H or U), target type (static, onset, flicker), and flicker frequency (8, 17, 33, 100 Hz). All possible factor combinations were presented in random order. Note that a stimulus flickering at 100 Hz was perceptually identical to a static stimulus. For the analysis, target identity was not further considered, yielding 40 trials for each combination of target type and flicker frequency.

Results

RTs. Mean correct RTs were calculated separately for each participant and factor combination, excluding outlier trials with RTs smaller than 200 ms or larger than 2000 ms (1.3% of all trials). The RTs were submitted to a 3x4 Repeated Measures ANOVA with the factors target type (static, flicker, or onset), and flicker frequency (8, 17, 33, 100 Hz). There was a significant main effect of both target type, $F(2, 22) = 8.29$, $p < .01$ with onsets found significantly faster than either a static, $F(1, 11) = 18.29$, $p < .001$) or a flicker, $F(1, 11) = 4.99$, $p < .05$) target. There was no difference in RTs between an onset and a motion onset ($F = 2$). There was also a main effect of flicker frequency, $F(3, 33) = 3.65$, $p < .05$. Moreover, the interaction between target type and flicker frequency was significant, $F(6, 66) = 2.57$, $p < .05$.

Errors. Mean percentage errors were calculated separately for each participant and factor combination. As can be seen from Table 4.1, the averaged error rates were relatively low (on average 3.9%), suggesting that most participants had no problem following the instructions keeping errors below 5%. A 3x4 Repeated Measures ANOVA showed a significant main effect of target type, $F(2, 22) = 8.01$, $p < .01$, due to participants making more errors when the target was a flickering than when it was either an onset or a static item. There was no difference in errors between onset and static target types. There was neither a main effect of flicker frequency, nor did it interact with target type (both $F < 1.5$). Thus, regarding target type, errors were higher in conditions in which the RT was slower, indicating the possibility of a speed accuracy trade-off.

Table 4.1.

Mean Percentage Errors for various refresh rates (Hz) in Experiments 5 and displacements (degrees) in Experiments 6 and 7.

	Target Type		
Flicker frequency / displacement	Static	Onset	Flicker / displaced
Experiment 5			
100 Hz	5.2	3.8	6.3
33Hz	5.6	3.5	5.4
17 Hz	4.2	5.4	8.3
8 Hz	5.0	3.3	6.7
Experiment 6			
0.09°	4.0	1.5	5.4
0.26°	4.8	2.1	3.5
0.52°	3.8	2.1	4.2
1.05°	4.8	1.5	2.9
Experiment 7			
0.09°	2.7	2.7	3.1
0.26°	2.3	4.0	1.7
0.52°	2.5	2.5	2.9
1.05°	3.8	1.5	3.5

Inverse-Efficiency Score. RTs were adjusted for errors by calculating inverse-efficiency scores, using the formula: inverse-efficiency scores = RT/((100-ER)/100) as suggested by Townsend and Ashby (1983). Figure 4.3 shows the inverse-efficiency scores as a function of flicker frequency with separate lines for each target type. As can be seen, a flicker target was not found any faster than a static target and flicker frequency did not affect search performance.

The mean inverse-efficiency scores for each participant was submitted to a 3x4 repeated measures ANOVA with the factors target type (static, flicker or onset) and flicker frequency (100, 33, 17, or 8 Hz) There was only a significant main effect for target type, $F(2, 22) = 10.6$, $p < 0.001$: Post-hoc LSD tests revealed that participants were on average 48 ms faster (based on the inverse efficiency score) in finding the target when it was an onset than when it was either a static or a flicker stimulus, with no difference between the latter two target types. Note that non-corrected RTs showed a small but significant advantage for flicker compared to static in the 17 Hz condition, $t(11) = 2.29$, $p < .05$, but this effect disappeared when correcting for errors, $t(11) = 0.65$, ns.

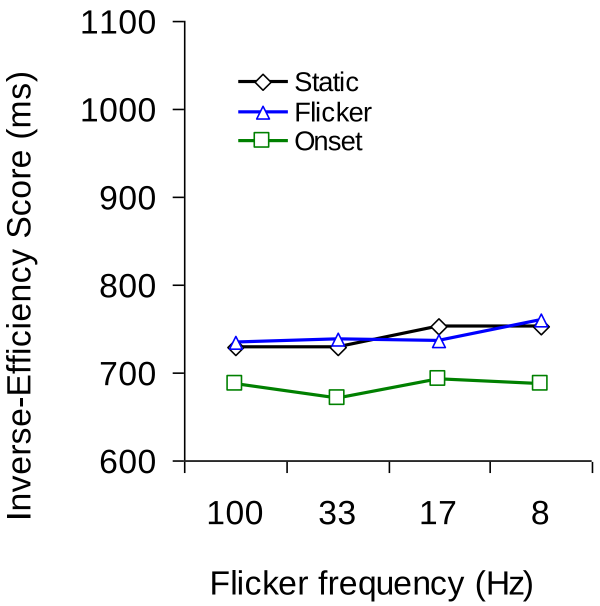

Figure 4.2. Mean Inverse-efficiency scores as a function of flicker frequency in Experiment 5, with separate lines for each target type.

Discussion

The results of Experiment 5 show that search does not become more efficient when the target letter flickered, as compared to when it was static. This indicates that a luminance flicker does not capture attention when flicker is not relevant to the search task. Thus, the present experiment suggests that the attentional effect found for the onset of jerky found in Experiments 3 and 4 is not due to flicker.

The findings contrast with those of Spalek et al. (2009), who showed that flicker could be effectively used to detect a target item. However, in their study the flicker defined the target item, making flicker relevant to the search task. Thus, participants were likely to have a top-down attentional set for the detection of flicker (Folk, Remington & Wright, 1994). In contrast, flicker was task irrelevant in the present experiment and so observers had no reason to set themselves to detect flicker.

This suggests that the visual system could effectively use flicker as a feature to guide search, but also that flicker does not automatically capture attention. The present study is similar to that of Pinto, Olivers and Theeuwes (2006), who asked participants to find if a vertical or horizontal line segment was present among slanting line segments. The items in the display flickered at different frequencies (between 2.86 and 6.67 Hz), but were irrelevant to the task. They found that flicker had no effect on task performance.

Experiment 6

Experiment 5 showed that abrupt luminance changes associated with flicker are not sufficient to capture attention. Thus, attention capture with jerky motion does not seem to be caused by the concurrent abrupt luminance changes. Experiment 6 tests whether capture by jerky motion is linked to the events that occur immediately at the beginning of search or whether it is linked to the continued jerkiness of motion. If capture is determined by changes to low level features, more than by a higher-level change in the dynamic status of an object, it might occur at a very early stage of processing (Donk & van Zoest, 2008; Kim & Cave, 1999; see Theeuwes, 2010, for a review). If, indeed, the RT benefit observed with jerky motion is due to bottom up capture, then "continued" jerkiness of motion might not be essential for attention capture.

In Experiment 6 therefore continued motion was smooth (100 Hz) after a first "jerky" displacement. More precisely, at display transition the motion stimulus was displaced by one step of 1.05, 0.52, 0.26 or 0.09° (factor displacement) and then remained stationary for 120, 60, 30 or 10 ms, respectively, in order to keep speed constant for all displacements. Thereafter motion was smooth. These initial displacements and their delays correspond spatio-temporally exactly to the motion refresh rates (8, 17, 33 and 100 Hz) used in Experiments 3 and 4 (i.e., the two experiments differed only with respect to whether the subsequent motion was smooth or jerky).

Method

Participants. Twelve undergraduates (1 male, 11 female, mean age 18.76) from the University of Warwick participated in return for course credit.

Apparatus, Stimuli, Procedure and Design. The apparatus, stimuli, procedure and design were the same as in Experiment 5, except that the flicker stimulus was replaced by a moving stimulus (see Figure 4.2). At display transition, the placeholder of the motion stimulus was deleted while the corresponding letter was redrawn at the new displaced location, where it remained still for a duration which varied proportionally to the size of the first displacement. The size of the initial displacement was either 0.09, 0.26, 0.52 or 1.05°, and the corresponding delay was 10, 30, 60 or 120 ms.

Thereafter the motion stimulus continued to move smoothly at 100 Hz on a circular path (radius = 1.3°) at the same constant speed of 8.7°/s, at which a full rotation took 960 ms. Note that the smallest displacement of 0.09° followed by the 10 ms delay corresponds to the smooth 100-Hz motion, thus in this condition there was no interruption after the initial displacement. Moving direction was randomly varied between clockwise and anti-clockwise.

Results

RTs. Mean correct RTs were calculated separately for each participant and factor combination, excluding outlier trials with RTs smaller than 200 ms or larger than 2000 ms (0.9% of all trials). Figure 4.4 shows the averaged RTs as a function of initial displacement with separate lines for each target type.

A 3x4 repeated measures ANOVA conducted on the mean correct RTs with the factors target type (static, moving, or onset), and initial displacement (0.09, 0.26, 0.52, or 1.05°) showed a significant main effect of target type, $F(2, 22) = 34.6$, $p <$

.001: Posthoc LSD tests revealed that overall, onset targets were found significantly faster than the moving targets, which in turn were found significantly faster than static targets (678, 710, and 773ms, respectively).

The two-way interaction was also significant, $F(6, 66) = 7.82$, $p < .001$. Three split-up 2x4 ANOVAs revealed that target type interacted with initial displacement between the static/moving pair, $F(3, 33) = 14.08$, $p<.001$, and between the onset/moving pair, $F\ (3,33) = 11.13$, $p <.001$, but not in the static/onset pair ($F < 2$). Separate Bonferroni adjusted t-tests revealed that the moving targets were found significantly faster than the static targets at all but the smallest 0.09° displacement – and significantly slower than onset targets at the 0.09° displacement (all $p < .001$). In other words, finding a smooth motion onset target with no initial displacement (0.09° displacement) was not different from finding a static target, whereas a jerky motion onset target with an initial displacement (1.05, 0.52, or 0.26° displacement) was found as quickly as an onset target.

Errors. Mean percentage errors were calculated separately for each participant and factor combination. As can be seen from Table 4.1, the averaged error rate was low (overall 3.4%). A 3x4 ANOVA with the factors target type and initial displacement revealed a significant main effect for target type, $F(2, 22) = 9.7$; $p < 0.001$, due to fewer errors in the onset condition than in the static and moving condition (1.7 vs. 4.7 and 3.0%, respectively). Overall errors showed a similar pattern to the RTs, ruling out speed-accuracy trade-off effects.

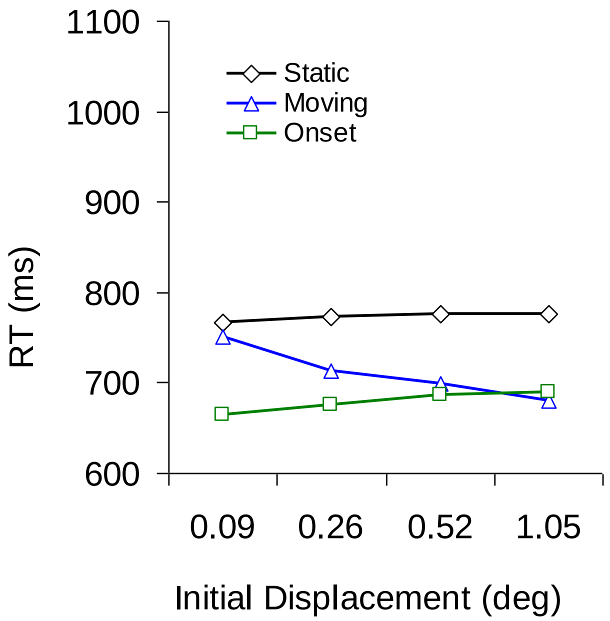

Figure 4.3. Mean correct RTs as a function of initial displacement in Experiment 6, with separate lines for each target type.

Discussion

Experiment 6 shows that attention capture by the onset of jerky motion depends entirely on the initial abrupt displacement. On the one hand, when the initial displacement was very small (0.09°), giving the impression of a smooth motion onset, then the moving stimulus had no processing advantage in comparison to the static stimulus. This result consolidates the findings from chapter 3, as it provides further empirical support for the absence of capture by the onset of smooth motion.

On the other hand, when the displacement was large (0.26, 0.52, or 1.05°) giving the impression of a jerky motion onset, then the moving stimulus had a clear processing advantage as compared to the static stimulus. The RT benefit was in fact (quantitatively) not distinguishable from the RT benefit to an onset target. This result is important, because it shows that continued jerkiness of motion is not necessary for attention capture, and that capture is mediated by the events that occur immediately at the beginning of search.

A direct comparison of Figure 4.1 and 4.4 shows that the pattern of results in this experiment closely resembles that of Experiment 3, except for the main effect of motion refresh rate (which was absent in the current experiment). It was suggested that this main effect is due to the continued jerkiness adding overall noise to the display, making search overall more difficult. The absence of such an effect in the current experiment supports this notion, as the subsequent use of smooth motion might have removed the perceptual noise in the current experiment.

Experiment 7

Experiment 6 showed that a brief disruption (i.e., a displacement followed by a delay) at the beginning of motion is sufficient to capture attention. One possible explanation could be that the initial displacement delays the perceived onset of motion, turning it into a temporally unique event that captures attention. Sunny and von Mühlenen (2011) postulated that the perceived delay could be caused by the interference from the other changes co-occurring in the display (i.e., the appearance of the onset and the segment removals), such that the initial displacement of the moving stimulus goes unnoticed because of this interference. This could have the effect that only the second displacement is noticed, which becomes the perceived onset of motion.

The fact that smooth motion onset without a delay (e.g., Sunny & von Mühlenen, 2011; von Mühlenen et al., 2005) does not capture attention supports this delayed motion onset account. Experiment 7 now presented a displacement without the subsequent motion, thus removing the delay. Under the delayed motion onset account it is hypothesized that no capture would occur when the motion onset is absent. Experiment 7 was in all respects identical to Experiment 6, except that the displaced stimulus remained stationary after the initial displacement.

Method

Participants. Twelve undergraduates (2 male, 10 female, mean age 19.2 years) from the University of Warwick participated in return for course credit.

Apparatus, Stimuli, Procedure and Design. The apparatus and stimulus were the same as in Experiment 6 except that the moving stimulus was replaced by a displaced stimulus. That is, one stimulus was displaced by 0.09, 0.26, 0.52 or 1.05°, but then instead of moving smoothly, it simply remained stationary (see Figure 4.2). The procedure and design were the same as in Experiment 6.

Results

RTs. Mean correct RTs were calculated separately for each participant and factor combination, excluding outliers (1.1%). Figure 4.5 shows RTs as a function of motion refresh rate with separate lines for each target type.

A 3x4 repeated measures ANOVA conducted on the mean correct RTs with the factors target type (static, displaced, or onset), and displacement (0.09, 0.26, 0.52, 1.05°) showed a significant main effect of target type, $F(2, 22) = 20.43$, $p <.001$: Posthoc LSD tests revealed that overall, onset targets were found significantly faster than the displaced targets, which in turn were found significantly faster than static targets (769, 804, and 836 ms, respectively). There was also a significant main effect of displacement, $F(3, 33) = 13.23$, $p<.001$.

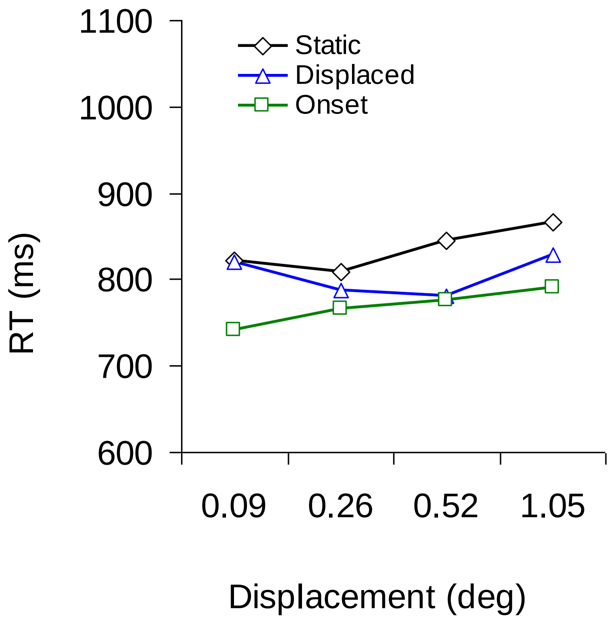

Figure 4.4. Mean correct RTs as a function of displacement in Experiment 7, with separate lines for each target type.

The two-way interaction was also significant, $F(6, 66) = 3.65$, $p <.01$ and three separate 2x4 split-up ANOVAs comparing each possible pair of target type levels found an two-way interaction in the static/displaced pair, $F(3, 33) = 3.24$, $p <.05$, and in the onset/displaced pair, $F(3, 33) =6.96$, $p <.001$, but not in the static / onset pair ($F< 2$). Separate Bonferroni adjusted t-tests revealed that the displaced targets were found significantly faster than static targets at displacements of .52 and 1.05° and significantly slower than onset targets at a displacement of 0.09°. To summarize, abruptly displaced targets were found increasingly faster with increasing displacement size.

Errors. Mean percentage errors (see Table 4.1) were calculated separately for each participant and factor combination. A 3x4 ANOVA with the factors target type and displacement did not reveal any significant main effect, but a marginally significant interaction, $F(6, 66) = 2.25$, $p = .054$. Overall errors showed a pattern similar to that of the RTs, ruling out speed-accuracy trade-offs.

Discussion

The results of Experiment 7 show that a small abrupt displacement of half a degree captures attention as strongly as an abrupt onset. This is contradictory to the delayed-onset hypothesis and it sheds new light on why jerky motion onset captures attention. Attention capture by motion onset reported by a number of studies that used jerky motion (Abrams & Christ, 2003; 2005; Christ & Abrams, 2008, Christ et al., 2008) seems to be caused by the first abrupt displacement and not by a higher level change in the status of an object from stationary to moving. This conclusion is further supported by the fact that the displacement was barely noticeable. When asked at the end of the experiment, ten out of twelve participants reported that they did not notice any displacement. The present findings provide further evidence for the role of a relatively small low level change in attention capture and are consistent with a bottom up model of attention capture.

Prima facie, these results are not in line with von Mühlenen et al.'s (2005) unique event account, according to which an abrupt displacement is not expected to capture attention as it co-occurs with other changes in the display. As such it puts abrupt displacement in the same category as abrupt onsets, which have been shown to capture attention even when they are not temporally unique. It therefore does not seem so far off to consider whether similar mechanisms are responsible for capture by both displacements and onsets. This will again be taken up in Experiment 9 and in the general discussion.

Experiment 8

Experiments 5-7 used absolute RT differences as an indicator for attentional capture, as did Abrams and colleagues (Abrams & Christ, 2003; 2005; Christ & Abrams, 2008; Pratt, Radulescu, Guo & Abrams, 2010) and Sunny and von Mühlenen (2011). However, a stronger test for capture would be to use search slopes instead of absolute RT differences (e.g., Simons, 2000). Experiment 8 therefore tested whether the capture effect for abrupt displacements was observed in the search slopes when presenting RT as a function of display size. Display size was systematically varied from 3, 5, to 7 items, and displacement was fixed at 0.52° (at which capture effect in Experiment 7 was numerically strongest).

Method

Participants. Thirteen undergraduates (7 male, 4 female, mean age 22.3) from the University of Warwick participated in return for course credit.

Apparatus and Stimuli. The apparatus and stimuli were the same as in Experiment 7, except for the following changes: The initial display contained either 2, 4 or 6 placeholders followed by the search display with 3, 5 or 7 letters. They were placed on the circumference of an imaginary circle (radius 12.5°) centred on fixation, such that neighbouring letters in the search display were always equidistant from each other.

Procedure and Design. Procedure and Design were the same as in Experiment 7, apart from some changes to the design: The number of stimuli in the display was systematically varied among 3, 5, and 7 items. Each display always contained one onset stimulus and one displaced stimulus, the rest was filled up with static stimuli, one, three, or five, depending on display size. Displacement size was fixed at 0.52°. Each participant completed 20 practice trials followed by 480 experimental trials. At every display size, the target was equally likely to be the onset, displaced or the static stimulus. The experiment systematically varied three factors: target identity (H or U), target type (static, displaced, onset), and display size (3, 5 and 7).

Results

RTs. Mean correct RTs were calculated separately for each participant and factor combination, excluding outlier trials with RTs smaller than 200 ms or larger than 2000 ms (1.7% of all trials). Figure 4.6 shows RTs as a function of display size with separate lines for each target type.

A 3x3 repeated measures ANOVA conducted on the mean correct RTs with the factors Target Type (static, displaced, onset), and Display Size (3, 5, 7) showed significant main effects for both target type, $F(2, 24)=23.26$, $p<.001$ and display size, $F(2, 24) = 126.87$, $p<.001$: Posthoc LSD tests revealed that overall, both onset and displaced targets were found significantly faster than static targets, while there was no significant difference between displaced and onset targets

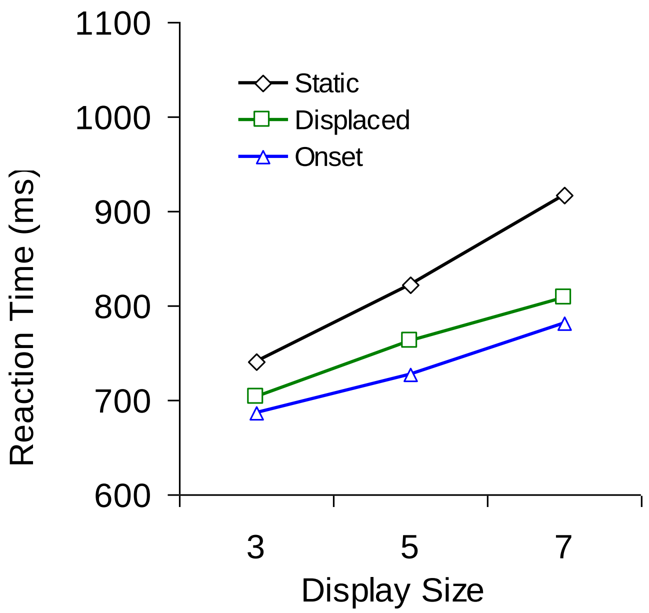

Figure 4.5. Mean correct RTs as a function of display size in Experiment 8, with separate lines for each target type.

The two-way interaction was also significant, $F(4, 48) = 4.62$, $p < .01$ and three separate 2x3 split-up ANOVAs comparing each possible pair of target type levels found a significant interaction for the static / displaced pair, $F(2, 24) = 7.16$, $p < .001$, and for the static / onset pair, $F\ (2, 24) = 9.43$, $p < .001$, but not for the onset /displaced pair ($F < 1$). This means, RT slopes in the displaced and onset condition did not differ from each other, but they were both faster than the static RT slope (26.0 and 23.6 vs. 44.3 ms/item, respectively).

Errors. A 3x4 ANOVA on mean percentage errors (see Table 4.2) with the factors target type and display size did not show any significant effects (all $p > .10$).

Table 4.2.

Mean Percentage Errors in Experiment 8 and 9

	Display Size		
Target Type	3	5	7
Experiment 8			
Static	1.7	2.6	1.9
Onset	1.7	0.2	1.4
Displaced	1.7	1.0	1.2
Experiment 9			
Static	4.7	3.3	2.7
Onset	2.6	2.6	2.4
Displaced	2.6	1.8	2.1

Discussion

Overall, the results of Experiment 8 confirm the finding of Experiment 7, showing that a displaced target captures attention as strongly as an onset target. There was no difference in the search slope between an onset and displaced targets and they were both less steep compared to static targets. Although the displaced and onset slopes were significantly reduced in comparison to the static slopes, one might note that they are steeper than what is expected under perfect capture conditions. However, there were always two simultaneous events (i.e., an onset and a displacement) that compete for attention, leading to an overall slope increase.

Sunny and von Mühlenen (2010) used search displays containing multiple simultaneous onsets that were task irrelevant and showed that only one onset is automatically prioritized during search. The fact that the slopes for onset and displaced targets were statistically equivalent suggests that both onsets and displaced items compete equally for attention. Therefore, on average, the onset item would be inspected first on half the trials while the displaced item would be inspected first in the other half. This explains not only the slope for RTs to onset and displaced targets, but also why they are both half as steep as the static slope.

The current results of Experiments 7 and 8 pose some difficulty for the new object account (Yantis & Jonides, 1996; Hillstrom & Yantis, 1994; see Egeth & Yantis, 199,7 for a review), according to which an abrupt onset captures attention because it signals the appearance of a new object. Most participants did not notice the abrupt displacements; it therefore seems very unlikely that they had perceived the displaced stimulus as a new object. Nevertheless, it is possible that the displacement together with the change in identity from a placeholder to letter constitutes a substantial change to its object file, which also requires attention, like the creation of a new object file (Kahneman, Treisman & Gibbs, 1992).

Previous studies have shown that the RT benefit for new objects is abolished when the amount of change in old and new objects is equated (Miller, 1989; Watson & Humphreys, 1995; also see Watson, Braithwaite & Humphreys, 2008, for a similar effect on visual marking). Moreover, Yantis and Gibson (1994) showed that when there was an ISI of more than 100 ms between the placeholder and the letter stimulus it captures attention in the same manner as an onset. In the current study, the ISI was always 0 ms, as a moving stimulus was always deleted and redrawn in the same refresh frame; but at a different location. It is possible that a displacement of 0.52° or

1.02° in the present Experiments 7 and 8 might have the same effect as a temporal gap of 100 or 133 ms in Yantis and Gibson's (1994) study.

Experiment 9

The results of Experiment 7 and 8 show that a small abrupt displacement of half a degree captures attention as strongly as an onset, in terms of overall RT benefit, as well as overall RT slope benefit. One conclusion could be that abrupt displacements represent a new class of events that capture attention. Within the framework of the unique event account (von Mühlenen et al., 2005), abrupt displacements would (like onsets) be an exception to the rule, as they capture attention irrespective of whether they are temporally unique or not.

The results of Experiment 7 suggested that the same mechanism might operate in attention capture by onsets and abrupt displacements. One possible single-mechanism explanation could be based on the new-object account (Hillstrom & Yantis, 1994), according to which capture occurs because both, onset and displaced items, require the creation of a new object file (Kahneman, Treisman & Gibbs, 1992). Another explanation could be based on Gibson's (1996a, 1996b) masking account, according to which capture occurs because the static items are forward masked by their figure-8 placeholders, giving the onset and the displaced item a head start in processing.

Experiment 9 is aimed at distinguishing between these two alternative accounts. It uses exactly the same method as Experiment 8, except that now the displacement occurred 60 ms before display transition. Because of the displacement, the new-object account would predict that capture occurs like in the previous experiments. However, the masking account would predict no capture, because the displaced item is now preceded by a placeholder at exactly the same location.

Method

Participants. Twelve undergraduate students (4 male, 8 female, mean age 21.5 years) from the University of Warwick participated in return for course credit.

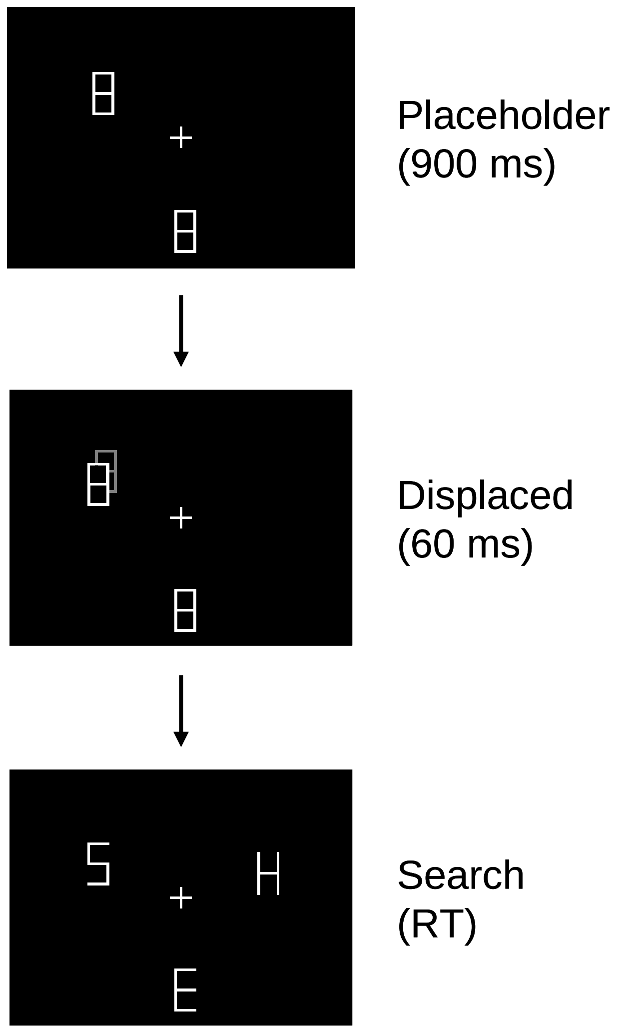

Figure 4.6. Example display for Experiment 9. Stimulus displacement by 0.52° occurred 60 ms before display transition. The grey placeholder in the displaced display was not visible.

Apparatus, Stimuli, Procedure and Design. The task and stimuli were the same as in Experiment 8, except that the displacement happened 60 ms before the display transition (see Figure 4.7). The procedure and design were the same as in Experiment 8.

Results

RTs. Mean correct RTs were calculated separately for each participant and factor combination, excluding outlier trials with RTs smaller than 200 ms or larger than 2000 ms (1.2% of all trials). Figure 4.8 shows RTs as a function of display size with separate lines for each target type.

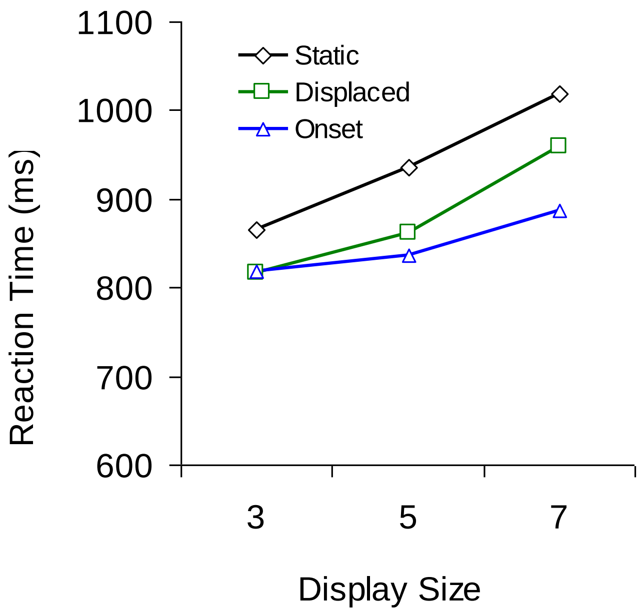

Figure 4.7. Mean correct RTs as a function of display size in Experiment 9 with separate lines for each target type.

A 3x3 repeated measures ANOVA conducted on the mean correct RTs with the factors Target Type (static, displaced, onset), and Display Size (3, 5, 7 items) showed significant main effects of target type, $F(2, 22) = 29.66$, $p < .001$ and display size, $F(2, 22) = 51.78$, $p < .001$: Posthoc LSD tests revealed that overall, onset targets were found significantly faster than displaced targets, which in turn were found significantly faster than static targets (847, 878 and 939 ms respectively).

The two-way interaction was also significant, $F(4, 44) = 3.46$, $p < .01$ and three separate 2x3 split-up ANOVAs comparing each possible pair of target type levels found a significant interaction for the static / onset pair, $F(2, 22) = 5.31$, $p < .01$, and for the onset / displaced pair $F(2, 22) = 3.5$, $p < .05$; but not for the static / displaced pair, $F(2, 22) = 0.61$, $p = .553$. The RT slope for static and displaced targets did not differ from each other, and both were larger than the slope for onset targets (38.8 and 35.8 vs. 17 ms/item, respectively).

Errors. A 3x3 Repeated measures ANOVA on the errors (see Table 4.2) with the factors target type and display size showed a significant effect for target type, $F(2, 22) = 4.03$, $p < .05$, due to higher error rate with static target compared to onset or displaced targets (4.0 versus 2.8 and 2.5%, respectively). Overall errors show a similar pattern to the RTs, ruling out speed-accuracy trade-offs.

Discussion

The results of Experiment 9 are consistent with the masking account, but not with the new-object account. According to the masking account the abrupt displacement should not capture attention because it was now masked by the preceding figure-8 placeholder. The masking account could in fact account for all capture effects observed in the present chapter (Experiment 6-8). Moreover, it also explains why the onset of jerky, but not smooth motion captures attention: When motion is smooth, there is greater overlap in locations between two frames of motion as compared to when the motion is jerky. Finally, the masking account also explains why the static flicker in Experiment 5 did not capture attention: The flicker item was masked like the static item because the item location did not change. To stretch these findings further, I believe that a similar mechanism operates in Yantis and Gibson (1994) and the present findings. It seems that a 133 ms gap is not long enough time to turn an object into a new object, at least not at a perceptual level. However, if figure-8s act as masks, a 133 ms gap might be long enough time to reduce or even remove the masking effect.

Indeed, this argument has already been made by Gibson (1996a), who showed that capture by an onset was abolished when the onset was masked. In the preliminary experiment, the items in the display were either all onsets or all no-onsets. In the no-onset condition, the effect of masking was studied by varying the brightness of the placeholders, while keeping the brightness of the final display the same. The results suggested that there was an overall RT difference between bright, dim and no-placeholder conditions in spite of them having the same final luminance. It was argued that masking by placeholders, both dim and bright, affected a stage of processing that is prior to selection.

In a second experiment, attention capture by an abrupt onset was put in the context of a masked placeholder. The results suggested that an onset captured attention only when presented simultaneously with bright placeholders, but not with dim, suggesting that capture results from better/earlier encoding of onsets when the distractors are masked. He suggested that the absence of a mask makes the abrupt onset available earlier for processing as compared to the other masked stimuli.

Based on these findings it is possible to argue that the display size attenuation with onsets need not result from bottom-up capture, but from an early advantage to the onset items that result from their better encoding (but see Yantis & Jonides, 1996, and Gibson's, 1996b, reply). This framework can be easily extended to include capture by an abrupt displacement because the displaced item appears at a location that was not occupied by a placeholder.

General Discussion

The current study presents five experiments attempting to explain attention capture by the onset of jerky motion (Abrams & Christ, 2003, 2005; Christ & Abrams, 2008, Christ, Castel & Abrams, 2008; Sunny & von Mühlenen, 2011), but not smooth motion (Sunny & von Mühlenen, 2011; von Mühlenen et al., 2005). Experiment 1 shows that flicker on its own without motion has no effect on attention. Whereas Experiment 2 shows that continued motion jerkiness is not essential, Experiment 3 and 4 suggest that subsequent motion might not be required at all to obtain a capture effect. In fact all results presented in this study can all be explained by the assumption that a single abrupt displacement is enough to capture attention.

There are a number of other studies that reported capture with smooth motion onset (Abrams & Christ, 2005; Franconeri & Simons, 2003; Skarrat, Cole & Gellatly, 2009; von Mühlenen et al., 2005). However, in all these studies the motion onset was temporally unique, starting before display transition, and hence the unique event account explains capture. Moreover, the results of Experiment 5 puts capture by abrupt displacement down to a better visual quality due to absence of masking (Gibson, 1996a).

The common principle is that the processed stimulus that becomes available first captures attention. Gibson (1996a), showed that capture by an onset was abolished when the onset was masked. He also suggested that the absence of a mask makes the abrupt onset available earlier for processing as compared to the other masked stimuli (but see Yantis & Jonides, 1996, and Gibson's, 1996b reply).

The masking account can in fact account for all capture effects observed in the present study. A stimulus captures attention when it is not preceded by a placeholder at exactly the same location. In Experiment 2, the moving stimulus captured attention, because of its initial displacement. In Experiment 3 and 4, the displaced stimulus captured attention for the same reason.

The masking account also well explains the absence of a capture effects in Experiment 1 and 5. In Experiment 1 the flicker stimulus did not capture attention because there was no temporal gap between the placeholder and the letter (i.e., the letter followed immediately after the placeholder). In Experiment 5, the displaced stimulus does not capture attention because there was a placeholder preceding the letter for 60 ms.

Moreover, masking also explains why the onset of jerky, but not smooth motion captures attention: When motion is smooth, there is greater overlap in locations between two frames of motion as compared to when the motion is jerky. To sum up, as long as the letter stimulus is separated from the pre-mask by a temporal or a spatial gap, it captures attention. For example, Yantis and Gibson (1994) showed that a 133 ms temporal gap was long enough to eliminate the masking effect (however note that in their interpretation, the 133 ms turned the stimulus into a new object).

The current results of Experiment 3 and 4 pose some difficulty for the new object account (Yantis & Jonides, 1996; Hillstrom & Yantis, 1994; See Egeth & Yantis, 1997 for a review), according to which only an abrupt onset capture attention because it signals the appearance of a new object. In the present study, the abrupt displacement could not have been perceived as a new object. Most participants did not notice the abrupt displacements; it therefore does not seem very plausible that they had perceived the displaced stimulus as a new object. Some researchers might argue that the displacement together with the change in identity from placeholder to letter constitutes a substantial change to the object file, which also requires attention (cf. Kahneman, Treisman & Gibbs, 1992).

The present results overall suggests that the same mechanism might operate in attention capture by onsets and displacements. Another explanation could be based on Gibson's (1996a, 1996b) masking account, according to which capture occurs because the static items are forward masked by their figure-8 placeholders, giving the onset and the displaced item, a head start in processing.

Conclusion

The present study allows for a new interpretation of Abrams and Christ's (2003) finding: In their study motion onset only captured attention because the motion was jerky. The present study suggests that this effect is due to the initial abrupt displacement of the moving item. The absence of capture with smooth motion (Experiment 4; von Mühlenen et al., 2005) refutes Abrams and Christ's motion onset account, according to which a motion onset should always capture attention. This leaves motion onset on a par with any other feature change, such as colour or luminance changes.

The core idea behind the unique-event account is that any sudden change is capable of capturing attention as long as it is temporally unique. The finding that an abrupt displacement captured attention the same way as an abrupt onset (despite being non-unique) is a new and interesting finding. It was speculated that they both might escape masking, either because there was no placeholder in the case of onsets, or because the placeholder was at a different location in the case of displacements. However, whether other exceptions can also be explained by this single masking mechanism or whether separate mechanisms are required remains an open question for future research.

Chapter 5: A change in the direction of motion captures attention, but only when it is unique.

Introduction

Motion is a very common feature in the visual environment; it is also an important feature that can be used to guide visual attention. For example, at the arrivals in the airport, people tend to instinctively use waving as an action to attract one another's attention. This is a good instance of one particular type of motion, like waving, standing out among other types of motion, like people walking about etc. Previous studies have shown that motion can be used as an effective cue in guiding search. In a visual search paradigm, McLeod, Driver and Crisp (1988) showed that the search for a conjunction of the features shape and motion proceeds in a parallel manner. However, since motion is a very common feature, it seems unlikely that all motion grabs attention in an automatic stimulus driven manner.

Indeed, research has shown that motion, in general, does not capture attention (e.g., Hillstrom & Yantis 1994; Yantis & Egeth, 1999). For example, Hillstrom and Yantis (1994) used motion that was either predictive or un-predictive of the target location. They found that participants used motion to guide attention to the target location when motion was predictive, but when it was not, a moving stimulus was not any easier to find than a stationary stimulus. An exception was when motion resulted in the appearance of a new object. Thus, research in general supports the view that motion per se does not capture attention.

More recently it has been suggested that motion captures attention, when they represent events that are behaviourally urgent. For example, Franconeri and Simons (2003, 2005) suggested that objects approaching an observer would represent such an urgent event, whereas objects moving away might not. In line with this idea, they showed that looming motion generally captures attention while receding motion does not. This result was supported by a number of other studies that showed that looming motion captures attention while receding motion does not (Takeuchi, 1997; Skarratt, Cole & Gellatly, 2009; von Mühlenen & Lleras, 2007).

An alternative account of capture is based on the idea that features suggesting animacy in the visual environment capture attention. Indeed, motion is a strong indicator of animacy and many studies have shown that certain patterns of motion lead observers to attribute animacy and causality to objects (Michotte, 1963; for a review, see Scholl & Tremoulet, 2000). Abrams and Christ (2003, 2005) showed that, although a continuously moving target was not easier to find than a static target, a motion onset target was. Their results suggest that the onset of motion captures attention because it indicates the presence of an animate object in the visual field. In two other studies they replicated this benefit for motion onset when comparing it with abrupt onsets (Christ & Abrams, 2008) and also when testing older people (Christ, et al., 2008).

There are, however, recent findings that in general question the validity of both behavioural urgency and animacy as explanations for attention capture. For example, Experiments 3 and 4 showed that motion onset does not capture attention when subsequent motion is smooth. They used a visual search task in which participants were asked to find targets "U" or "H" among distractor letters. The motion refresh rate was systematically varied from 100 (very smooth) to 8 Hz (very jerky). They showed that motion onset did not capture attention when motion was smooth but it did when motion was jerky. These findings suggest that the capture effect by motion onset can be put down to the low refresh rate and argue for the role of low level change signals in mediating attention capture (Sunny & von Mühlenen, 2011).

Further support for the role of low level mechanisms in attention capture is offered by the unique event account, which emphasize the role of temporal uniqueness in capture. von Mühlenen, Rempel and Enns (2005) showed that capture occurs when an event happens just before or after but not together with display transition (i.e., when a placeholder display changes to the search display). It was reasoned that the temporal uniqueness makes the low level change signals stronger, making them harder to ignore. These results suggest that lower level change signals are more critical in driving attention capture, than higher level object changes.

Recently however, more evidence has emerged that suggests that higher level expectancy in motion plays a role in capture. For example, an unexpected change in motion of an object that implies an internal energy source was shown to capture attention (Howard & Holcombe, 2010; Pratt, Radulescu, Guo & Abrams, 2010). In both the studies, change was defined in terms of a change in direction. It is possible that direction change is a strong low level signal that could capture attention. It has previously been shown that low level luminance changes, like flicker per se do not capture attention (Pinto, Olivers & Theeuwes, 2006; Experiments 5 and 9). Nevertheless, a different kind of motion that allowed a greater disruption might lead to capture. Experiments 3 and 4, the path of the motion onset stimulus was continuous, with the moving stimuli following a circular path. This continuity, along with smooth 100 Hz motion might not have left room for any low level disruption. In the present context, by 'disruption' I mean an abrupt change to the motion path.

Experiment 10

Experiment 10 aimed to test whether or not attention was captured by a change in motion direction. The basic methodology was the same as in Chapter 3 as it offers a platform to test the effect of direction change against the baselines of static and onset items. The type of motion was changed from circular to linear (back and forth), with a direction change every 10, 30, 60 or 120 ms. The motion was always smooth and the stimuli moved at a constant speed. I hypothesise that the extent of attentional capture will change as a function of the time of the first direction change.

Method

Participants. A group of twelve undergraduates (5 male, 7 female, mean age 18.8) from the University of Warwick participated in return for course credit. All of them reported normal or corrected to normal vision and were naïve to the purpose of the experiment.

Apparatus and Stimuli. The participants were seated in a dimly lit sound attenuated room in front of a 19” CRT monitor at a distance of approximately 57 cm. The monitor was driven at 100 Hz at a resolution of 1024 x 786 pixels. The experiment was controlled by an IBM-PC compatible computer using custom written software. Participants' responses were recorded using left and right arrow keys on a standard keyboard.

Stimuli consisted of a fixation cross, figure-8 placeholders, and letters, presented in grey drawn on a black background. The fixation cross had a size of 0.6° of visual angle and was presented at the centre of the screen. The figure-8 placeholders and letters subtended 1° by 2° and were made of seven line segments (length 1.0°, thickness 0.13°). The letters were 'H', 'U', 'S' and 'E' and were made by removing the corresponding line segments from the figure-8. Stimuli were placed on the three imaginary corners of a randomly oriented equilateral triangle centered on fixation (fixation-letter distance was 12.5°). Letters in the search display were stationary or moving back and forth. The moving stimulus travelled 1.05°, 0.52°, 0.26° or 0.09° and then changed the direction by 180°. The direction change was in cycles of 120, 60, 30 or 10 ms oscillation for amplitudes of 1.05°, 0.52°, 0.26° or 0.09° respectively. This oscillation was repeated until the participant responded wherein the trial ended or after 10 seconds had elapsed. Motion refresh rate was always 100 Hz, giving the impression of smooth motion and the motion speed was 8.7°/s. Motion direction was clockwise or anticlockwise - orthogonal to an imaginary line connecting the centre of the letter to the fixation.

Procedure and Design. A trial started with the presentation of a preview display that consisted of a fixation cross and two figure 8 place-holders. After 960 ms, the preview display was followed by the search display which always contained three letters. The static and moving letters were revealed by deleting the irrelevant line segments from the corresponding place-holders, whereas the onset letter appeared at the previously unoccupied location. Stimulus oscillation began when the placeholders changed to letters (see Figure 5.1).

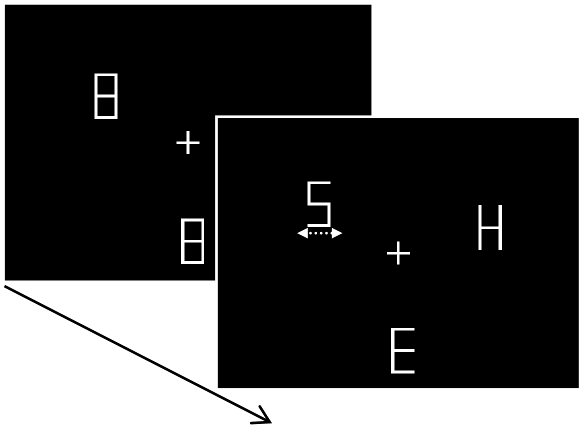

Figure 5.1. Example display in Experiment 10. Stimulus movement began when the placeholders changed to the letter stimuli. Here, the target letter 'H' is an onset, 'S' is moving and 'E' is static.

Participants were asked to look for ‘H’ and ‘U’ targets among ‘S’ and ‘E’ distractors and to respond using the left and right arrow keys on the key board. Half of the participants used the left arrow for H and right arrow for U, and vice versa for the other half. They were instructed to respond to the target as fast as they could whilst trying to make not more than 5% errors. The search display stayed on until the participant responded or 10 seconds had elapsed. In the instance of wrong responses immediate feedback was given on the screen reading “error” and participants had to press the space bar to continue the experiment. Otherwise the next trial started after an interval of 1 second. Each participant completed 20 practice trials followed by

480 experimental trials. The experimental trials were divided into 10 blocks of 48 trials each, with short breaks (10 seconds) between blocks.

The experiment systematically varied three factors: target identity (H or U), target type (static, onset, moving), and oscillation (10, 30, 60, or 120 ms). All possible factor combinations were presented in random order. For the analysis, target identity was not further considered.

Results

RTs. Mean correct RTs were calculated separately for each participant and factor combination, excluding outlier trials with RTs smaller than 200 ms or larger than 2000 ms (1.5% of all trials). Figure 5.2 shows RTs as a function of oscillation (ms) with separate lines for each target type. As can be seen, search time for a static target was slowest while those for an onset target were fastest. In comparison, RT to a moving target was overall faster than to a static target but slower compared to an onset target.

Individual mean RTs were submitted to a 3x4 repeated measures ANOVA with the factors target type (static, onset, moving), and oscillation (10, 30, 60, or 120 ms). There was a significant main effect of target type, $F(2, 22) = 20.66$, $p < .001$: Posthoc LSD tests revealed that onset targets were found significantly faster than moving targets, which in turn were found significantly faster than static targets (702, 770, and 828ms, respectively). The main effect of oscillation was not significant $F < 1$, however the interaction between target type and oscillation was significant $F(6, 66) = 2.77$, $p < .01$.

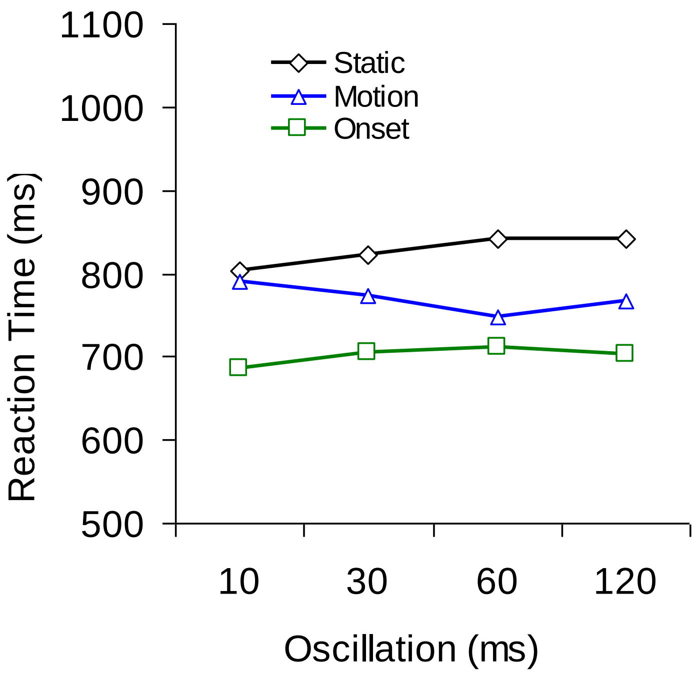

Figure 5.2. Mean correct RTs as a function of motion refresh rate in Experiment 10, with separate lines for each target type.

To further explore the 2-way interaction, three separate 2x4 split-up ANOVAs were conducted comparing each possible pair of target type levels. A significant interaction was found in the static/moving pair, $F(3, 33) = 3.84$, $p < .01$, and in the onset/moving pair, $F(3, 33) = 3.57$, $p = .05$, but not in the static/onset pair ($F < 1$). In Figure 5.2, the static line appears to be parallel to the onset line, but not to the moving line. Separate Bonferroni adjusted t-tests revealed that moving targets were found significantly faster than static targets at all but 10 ms oscillation, which was perceptually very similar to no oscillation (all $p < .05$). Moreover, there was no significant difference between an onset and moving target at 60 ms oscillation suggesting strongest capture at that temporal cycle. RT to a moving target was faster than RTs to a static target at all rates of oscillation other than 10 ms, at which the target appeared more or less static. The capture effect was strongest at 60 ms where the RT to a moving target was not significantly different from RT to an onset target. To summarize, a direction change captured attention even at the small temporal cycle of 30 ms.

Table 5.1.
Mean Percentage Errors in Experiment 10

	Target Type		
Oscillation	Static	Onset	Moving
10	3.8	2.5	3.5
30	4.0	2.1	3.8
60	3.1	2.7	2.9
120	3.3	3.1	3.5

Errors. Mean percentage errors (see Table 5.1) were calculated separately for each participant and variable combination. A 3x4 ANOVA with the factors target type and oscillation did not reveal any significant main effects or their interaction (all $F \leq 1$).

Discussion

In the present experiment, it was tested whether motion onset captures attention when the motion is oscillatory. It was hypothesized that the absence of capture observed Chapter 3 is at least partly due to the non-disruptive nature of smooth circular motion. The results showed a definite prioritization of oscillatory moving stimuli as compared with static stimuli. Moreover, the capture effect increased with larger oscillation, almost equaling capture by onsets at 60 ms oscillation[5].

Prima facie, the results suggest that motion onset captures attention when the motion path is oscillatory. However, the key to capture in this experiment might be a change in direction, rather than the onset of motion. This claim is supported by findings from Chapters 3 and 4 in which 100 Hz motion as used in the present experiment did not capture attention and the findings of Howard and Holcombe (2010) as well as Pratt et al. (2010) who showed that unexpected changes in the direction of motion captures attention. However, there are important differences between the present study and the studies that looked at unexpected changes to motion direction.

For example, Howard and Holcombe (2010) used an object tracking paradigm where participants were asked to report the orientation of one of the two objects (referred to as the queried target as opposed to the non-queried target) they were tracking. The objects that were tracked bounced against four invisible walls, changing the motion path. They found that when the target orientation was queried within 200 ms of the last bounce of a non-queried target, error rates were higher for the queried target. They suggested that the bounce of the non-queried target captured attention, resulting in an attention cost for the queried target. However, this did not occur when the targets bounced against a wall that was visible. They concluded that

[5] At 120 ms oscillation, the capture effect seems to reduce as the RT to a moving target is significantly slower than RT to an onset target. We think that this might be due to attention being captured by the abrupt onset item before the first direction change happened.

only bounces against an invisible wall can be considered as unexpected and thus capture attention.

In a similar experiment, Pratt et al. (2010) showed that dynamic changes to objects were detected faster when they occurred following an unexpected rather than expected change in motion. For example, when an object unexpectedly changed its motion direction or speed, it captured attention, but did not when the change in speed or motion direction was a result of a collision with another object or the boundary. They proposed that only unexpected changes indicate an internal energy source and thus animacy and concluded that animate rather than inanimate changes (in motion) capture attention.

The oscillatory motion used in the present study is more similar to the unexpected motion used by both Howard and Holcombe (2010) and Pratt et al. (2010) than the expected motion because in the present study, there was no physical object against which the moving object collided to initiate a direction change. Thus it is possible that the same mechanism operates in both the present experiment as well as the two studies mentioned above.

Experiment 11

Experiment 11 was designed to test other factors that might mediate attentional prioritization of a motion onset stimulus that changes direction. For example, when the direction change is more gradual, maybe the prioritization is eliminated. Moreover, it has already been shown that speed has an effect on capture, with faster stimuli demonstrating stronger capture (Pratt et al. (2010). In Experiment 11, therefore, there were two different types of direction change (gradual, abrupt) and two different speeds (fast and slow). The moving distance was 0.52° in slower speed whereas it was 1.02° with faster speed. Thus, the change in direction happened at a uniform oscillation of 120 ms from the onset of motion. This method will also help to determine if the capture effect in Experiment 10 was affected by the distance moved by the object before a direction change occurred. In contrast to Experiment 10, the stimulus moved in its central axis, meaning the first direction change occurred at 60 ms with every subsequent change following a 120 ms cycle.

Method

Participants. Twelve students from the University of Warwick (3 male, 9 female mean age, 19.8 years) participated in return for £5. All reported normal or corrected to normal vision and were naïve to the purpose of the experiment. None had participated in Experiment 10.

Apparatus and Stimuli. The apparatus and stimuli were similar to that of Experiment 10 except for the following differences. There were two different speeds- fast (8.7°/s) and slow (4.3°/s); and two types of motion change (gradual and abrupt). When the direction change was abrupt, the motion speed was constant over the oscillatory cycle, but when it was gradual motion speed decreased considerably before the direction change happened. As in Experiment 10, Experiment 11 also used linear motion. However, unlike Experiment 10, the direction of motion was randomly assigned (between 0 to 359°). In Experiment 11, the motion path was an arc, and was horizontal moving from left to right or right to left. The arc formed the part of a circle with a radius 1.3° in visual angle.

Procedure and Design. Procedure and design were similar to that of Experiment 10, except for the following changes. Instead of systematically varying oscillation from 0.09° to 1.02°, speed and oscillation type with two levels each was varied. The two levels, slow & fast and gradual & abrupt were fully factorially combined. Thus, the independent variables were target type (static, moving and onset), oscillation type (gradual and abrupt) and speed (fast and slow).

Results

RTs. Mean correct RTs were calculated separately for each participant and factor combination excluding outliers (1.3%) for Experiment 11a and 11b (see Figure 5.3). These were presented to a 2x3x2x2 with the factors experiment (11a or 11b) as a between subjects factor and target type (static, moving, onset) oscillation type (gradual or abrupt) and speed (fast, slow) within subjects. There was only a main effect of target type $F(2, 20) = 16.99$, $p<.001$. Posthoc LSD tests showed that a both an onset (740 ms) and a moving target (753 ms) were found faster than a static target (814 ms). There was no difference in RTs between an onset and a moving target.

Errors. Mean percentage errors are presented in Table 5.2. An ANOVA on the errors with the same factors as in RT did not reveal any significant effects (all p >.1).

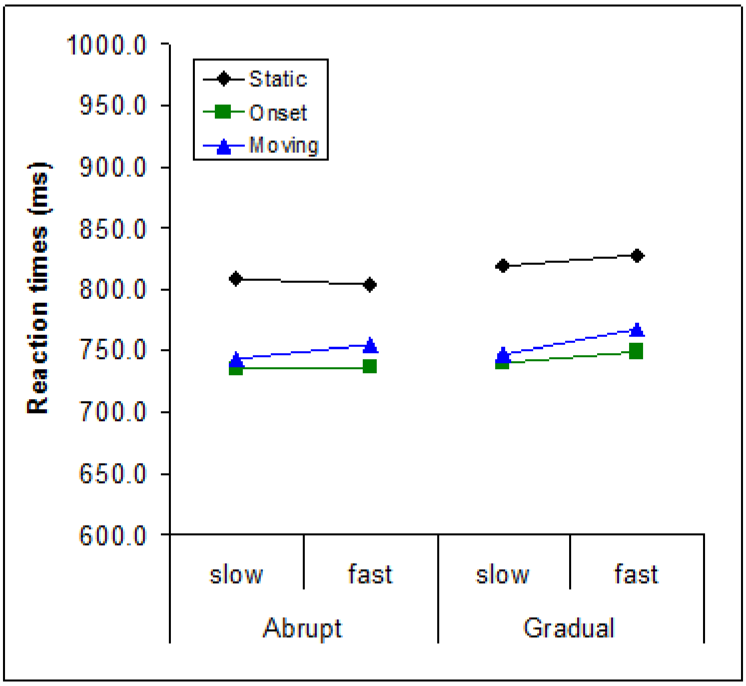

Figure 5.3. Mean correct RTs as a function of motion refresh rate in Experiment 11, with separate lines for each target type.

Table 5.2.

Mean Percentage Errors in Experiment 11

	Slow		Fast	
Target Type	Abrupt	Gradual	Abrupt	Gradual
Static	3.1	1.5	2.5	1.6
Moving	1.9	2.1	1.7	1.9
Onset	2.1	1.9	1.9	1.9

Discussion

The present experiment showed that speed and direction change (gradual or abrupt) had no effect on attention capture. Overall the results replicate the findings from Experiment 10, suggesting that a change in motion direction captures attention. This is in line with the findings of Pratt et al. (2010) as well as Howard and

Holcombe (2010) showing that an unexpected change in motion direction captures attention. The present results however have shown that a change in direction captures attention even when it is not ‘unexpected’.

Moreover, it was also shown that that speed does not have any effect on capture by oscillating stimuli. In contrast, Pratt et al. (2010) showed that the capture effect is stronger at higher speed, but their effect with an increase in speed was independent of a change in direction. Even though there is no RT difference between animate and inanimate change in Pratt et al.’s study using a speed of ~ 4°/s, in the present study, there is an RT difference between static and direction change using stimuli moving at a similar speed. This could be because direction change captures attention irrespective of the speed of motion. Hence, at both speeds, capture must have been strong. That is, if continued changes in direction capture attention, then the capture effect will remain the same irrespective of the speed. Moreover for capture effect that is mediated by temporal uniqueness, there was no variation in the time the direction change happened. That is, irrespective of the speed, the direction change always occurred 120 ms after display transition and hence the lack of change in the capture effect.

Similarly, the capture effect was unaffected by whether the direction change happened gradually or abruptly. This also points towards the robustness of capture, suggesting that capture by a change in direction does not depend on whether such a change happens gradually or abruptly. Overall, the results suggest that direction change is a rather robust cue and captures attention, irrespective of motion speed or abruptness of the direction change.

Experiment 12

The results from Experiments 10 and 11 suggest that a change in direction captures attention. However, these findings were based on overall RT measures. A stronger test of capture can be obtained by measuring search slopes. Thus, Experiment 12 was like Experiment 10, but with a display size variation. If the change in direction captures attention, a slope difference between the motion onset and static conditions would be expected; however if there is no capture, no slope difference will be expected. The abrupt onset was removed so that a possible capture effect with motion onset may not be attenuated by the presence of an abrupt onset.

Method

Participants. Twelve first year undergraduate students from the University of Warwick participated in return for course credit (5 male, 7 female, mean age 20.1). All of them reported normal or corrected to normal vision and were naïve to the purpose of the experiment. None of them participated in Experiment 10 or 11.

Apparatus and Stimuli. The task and stimuli was comparable to that of Experiment 10, except for the following changes. There were either 3, 5 or 7 figure-8 placeholders that subsequently changed to letters. They were placed on the circumference of an imaginary circle (radius 12.5°) centred on fixation such that the letters were equidistant from each other.

Procedure and Design. The procedure and design was similar to that of Experiment 10 except for the following changes. At the transition from placeholder to search, the figure-8 were replaced by letters (static) and one of the letters started moving in a 0.52 degree oscillation. Each display only contained one moving stimulus; the rest of the display was filled with static items. Each participant completed 20 practice trials followed by 480 experimental trials, divided into 10 blocks of 48 trials each, with short breaks between blocks. The motion onset item was no more likely to be the target than the static item. Thus, the experiment systematically varied two factors: target type (static, moving), and display size (3, 5 and 7).

Results

RTs. Mean correct RTs were calculated separately for each participant and factor combination, excluding outliers with RTs smaller than 200 ms or larger than 2000 ms (1.2 % of all trials) (see Figure 5.4). A 2x3 ANOVA with the factors Target Type (static, moving), and Display Size (3, 5, 7) showed a significant main effect of target type, $F(1, 12) = 29.3$, $p < .001$ because it took significantly longer to find a static target as compared to a moving target (849 ms vs. 749ms). There was also a main effect of display size, $F(2, 24) = 107.07$, $p < .001$, due to an overall increase of 39 ms/item with increasing display size. Most importantly, the two-way interaction between target type and display size was also significant, $F(2, 24) = 13.39$, $p < .001$ because the search slopes were significantly larger for static than for moving targets

(52 ms vs. 26 ms/item). This suggests that it was easier overall to find a moving target compared with a static target.

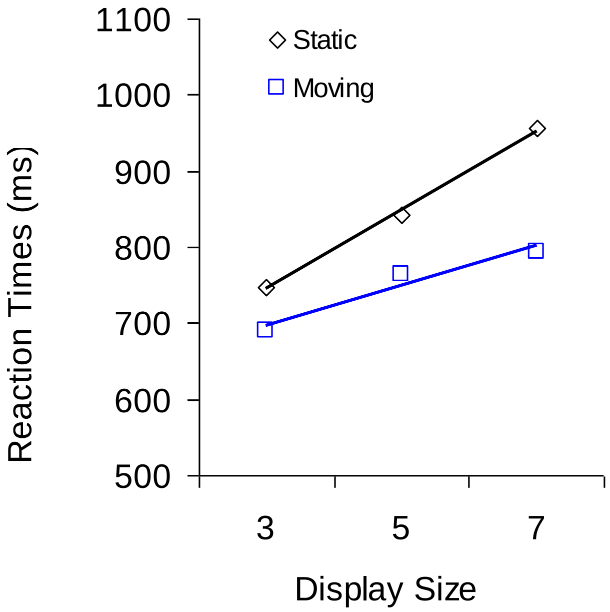

Figure 5.4. Mean correct RT as a function of display size (3, 5 or 7) in Experiment 12, with separate lines for target that was static or moving.

Table 5.3.

Mean Percentage Errors in Experiment 12 for each target type and display size

	Target Type	
Display Size	Static	Moving
3	3.9	4.2
5	3.1	3.7
7	2.3	3.9

Error. Mean percentage errors are presented in Table 5.3. A 3x4 ANOVA with the factors target type and motion refresh rate showed neither significant main effects or interaction effects of either target type, or display size (all p >.1).

Discussion

The present experiment tested the effects of display size on finding a target that happens to change its motion direction. The results showed that, compared with a stationary target, search slopes were significantly different for a motion onset target when it changes direction. Overall, the results suggest that a change in direction captures attention. This finding confirms that the RT benefit observed for motion onset targets in Experiment 10 and 11 results from capture of attention rather than perceptual factors. It also suggests that attention capture by motion onsets in the present study and other studies using oscillatory motion is due to the direction change that co-occurs with the motion rather than to the onset of motion.

Previous studies using oscillatory motion onset also support the current findings. For example, Hillstrom and Yantis (1994) used oscillatory motion onset (Experiment 3, late motion condition) and showed that it captures attention. However, they interpreted these findings as capture by a new object. They used hierarchical stimuli and used oscillatory motion to separate a local letter from the others. They argued that this separation from the group results in a new object, which in turn captures attention. They ruled out the role of motion by showing that when motion started at the beginning of the placeholder display there was no capture. However, in conjunction with the data from the present experiment, it seems that capture must have resulted from a change in direction that happened every 100 ms after the onset of the search display.

Similarly, Franconeri and Simons (2003) showed that oscillatory motion, along with other types of motion, capture attention. However, it is not clear whether the capture effect observed in their study resulted from a change in direction because their motion was also temporally unique. More recently, Cosman and Vecera (2010) showed that capture by motion onset is modulated by perceptual load. They found that motion onset captures attention only under conditions of low load, but not high load. They used oscillating motion with motion onset starting 100 ms prior to the display transition.

General Discussion

In three experiments, the present chapter clearly demonstrates that a change in the direction of motion captures attention. In Experiment 10, it was shown that the RT benefit for motion onset can be systematically strengthened by varying the oscillation of the motion onset. Experiment 11 replicated this finding and also showed that the capture effect does not depend on either the speed or the abruptness of the direction change. A strong RT benefit was observed with both a slow and fast speed and with a gradual and abrupt change in the direction. Experiment 12 showed that this RT benefit is indeed due to attention capture as there was a significant difference between search slopes for a static and a direction change target. The results clearly indicate that a change in the direction of motion captures attention.

The present study also lends support to the claims in Chapters 3 and 4 that motion onset per se does not capture attention. When motion onset is smooth, using high refresh rates, and without any changes in direction capture was not observed.

However, when it was jerky, using a low refresh rate, the jerkiness led to capture Chapters 3 and 4. Later studies showed that this capture by jerky motion did not result from increase in low level luminance changes, but from the abrupt displacement that happens at low refresh rates. The current chapter further reinforces the finding that motion onset per se does not capture attention, but a change in the direction of motion does.

Chapter 6: Attention Capture by Abrupt onsets: Revisiting the priority tag model

Introduction

Attention capture by abrupt onsets is a robust and a fairly undisputed finding. It has been replicated many times using various methodologies (e.g., Yantis & Jonides, 1984; Theeuwes, 1991; Todd & van Gelder, 1979). The most commonly used methodology is the *placeholder search paradigm,* where a preview display consisting of figure-8 placeholders is followed by a search display consisting of letters, along with a new letter at a previously un-occupied location (Yantis & Jonides, 1984). Participants search for a pre-specified target letter among various distractor letters. It is generally found that RTs are faster when the target is a new item (the *onset item*) as compared to when it is one of the old items (the *no-onset item*s). Typically RTs increase as a function of display size for no-onset targets while they do not increase for onset targets, suggesting that abrupt onsets capture attention (Jonides & Yantis, 1988) even when the target type (being an onset or no-onset) is irrelevant to search. They also showed that singletons defined in dimensions such as colour or luminance do not capture attention when they are task irrelevant, implying that capture by an onset is somehow special.

Even though capture by abrupt onsets has been a fairly robust finding, there was a controversy about the mechanism underlying this form of attention capture. According to Hillstrom and Yantis (1994), an abrupt onset constitutes the appearance a new object in the visual field and instantiates the creation of an object file (cf. Kahneman, Treisman & Gibbs, 1992), which requires the allocation of attention to the location of the object. Hillstrom and Yantis (1994) used letters that were perceptually new, but did not have an abrupt onset and showed that capture was mediated by the status of the letter as new rather than by their abrupt onset (also see Christ & Abrams, 2006, for a similar finding using a different method). Further support for the new object account comes from studies showing that illusory objects can also capture attention as long as they are perceived as new (Rauschenberger & Yantis, 2001; Yeshurun, Kimchi, Shashoua & Carmel, 2009). However, the placeholder search paradigm remains the predominant methodology used to study onset effects.

Several alternative accounts have been proposed to account for the RT benefit with abrupt onsets. One of them is based on the fact that, in most studies using a placeholder search paradigm, there is more local luminance change associated with the appearance of the onset letter as compared to the appearance of a no-onset letter. For example, Miller (1989) showed that when the overall change in luminance was held constant between the onset items and the no-onset items (i.e., the number of line segments that were deleted to form the no-onset letter were the same as the number of segments that made up the onset letter), onsets did not capture attention.

Further support for this claim was provided by Watson and Humphreys (1995) who showed that, as long as the overall change in luminance was kept constant, an increase in luminance had the same attentional effect as a decrease in luminance. However, other studies have found that attention capture by new objects cannot entirely be accounted for by changes in luminance. For example, Enns, Austen, Di Lollo, Rauschenberger, and Yantis (2001) showed that a new object with low contrast was found faster than an old object that underwent a large luminance change. Moreover, Gellatly, Cole and Blurton (1999) showed that a new object captured attention even when it was equiluminant with the background.

Another explanation for the onset effect was provided by Gibson (1996a) who argued that an abrupt onset captures attention because it is available earlier than the no-onset items for selection because of their better visual quality. In a series of experiments, he was able to show that search was faster in all-onset displays as compared to all no-onset displays suggesting that the placeholders that precede the no-onset letters might act as a pre-mask.

The mask had the effect of slowing down the processing of the no-onset item, in comparison to the onset item, which is not masked. Attention is then simply allocated to the item that is first available. Therefore, capture was put down to faster stimulus encoding rather than its status as a new object (but also see Yantis & Jonides, 1996; Gibson, 1996b). However, the masking account has been rejected as an explanation for the onset effect on the grounds that no RT difference is observed between onset and no-onset stimuli using a detection task if attention is already allocated to their location (Yantis & Hillstrom, 1994; Yantis & Jonides, 1984). It is usually argued that the onset effect results from an attentional advantage to the onset items rather than a sensory deficit suffered by the no-onset items.

Further evidence for the special status of onsets in attention capture comes from the finding that up to four onsets are automatically prioritized in visual search (Yantis & Johnson 1990; Yantis & Jones, 1991). Yantis and Johnson (1990) used a placeholder search paradigm with various display sizes (for example, 6, 8, 12, and 16 in Experiment 3). In addition every display had an equal number of onsets and no-onset items. For example, in their Experiment 3, every trial started with the presentation of eight placeholders. After 1000 ms, all placeholders changed to letters and at the same time new letters were added to the display such that the number of old and new objects in the display was the same. The target was an onset on half the trials and a no-onset item on the other half of trials.

They found that the type of target (onset or no-onset) interacted with display size between 6 and 8 but not between 8 and 16. They took this as indirect evidence for participants selectively searched through up to four onsets before searching through the remaining items in the display. They concluded that all onsets receive a priority tag, enabling search through about four items before the tags decay over time.

Consistent with this idea that search times are directly linked to the rate of information extraction, Yantis and Jones (1991) showed that the number of items that was prioritized was reduced from four to three when the visibility of the stimuli was decreased. The findings of Yantis and colleagues (Yantis & Johnson, 1990; Yantis & Jones, 1991) were surprising if one considers that the onset items were not more likely to be the target than the no-onset items. Their findings also spoke against a salience based account of capture, which assumed that capture effects are rather short lived allowing attention to be quickly disengaged (e.g., Donk & van Zoest, 2008; Kim & Cave, 1999).

In order to get a better estimate of the number of onsets that are automatically prioritized in a search task, it would be better if the number of onsets is systematically increased without a change to the overall display size. This way, if

RTs increase with an increase in the number of onsets in the display, it can be more readily attributed to capture by multiple onsets.

Priority tag model

For simplicity, the following priority tag model assumes that search operates as a serial process.[6] In this model, the expected number of comparisons that have to be done before the target is found is represented by y, which is determined by three factors, namely, the display size n, the number of onsets x, and the number of priority tags m. Irrespective of whether the target is an onset or not, the expected number of comparisons y should generally always increase with display size n. However the effect of the number of onsets x depends critically on the number of priority tags m. In the following, y is calculated separately for when $m \leq x$ and for when $m > x$. The calculation of y also depends on whether the target is an onset or a no-onset item.

Equation 1 gives the expected number of comparisons y required to find the target when the target is an onset and the number of priority tags is smaller than or equal to the number of onsets ($m \leq x$).

$$y(m; n, x) = \frac{m}{n} . \frac{m+ 1}{2} + \left(1 - \frac{m}{x}\right)\left(m + \frac{n-m+1}{2}\right), for\ m\ \leq x \quad (1)$$

According to the priority tag model, a subset of m onsets (the *priority set*) is first searched and the search process terminates when the target is found. This is represented in the left part of Equation 1, where the probability that the target is in the priority set m/x is multiplied by the expected number of comparisons required to find the target in that set $(m+1)/2$. When the target is not part of the priority set,

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[6]For a discussion of serial and parallel processing see Nakayama and Silverman (1986) and Townsend (1971, 1990)

search continues through the remaining items (the *no-priority set*), irrespective of whether these are onset or no-onset items. This is represented in the right part of the Equation 1, where the probability that the target is in the no-priority set 1–*m*/*x* is multiplied by the expected number of comparisons required to find the target in the no-priority set. This latter expected number of comparisons consists of the sum of comparisons made when searching through the entire priority set *m* and the comparisons required to find the target in the non-priority set *n*-(*m*+1)/2. Equation 1 can then be reduced to

$$y(m;\ n, x) = \frac{n+m+1}{2} - \frac{mn}{2x}, for\ m \leq x \qquad (1a)$$

Equation 2 gives the expected number of comparisons *y* required to find the target when the target is an onset and the number of priority tags is greater than the number of onsets ($m > x$);

$$\mathrm{y(m; n, x)} = \frac{\mathrm{x+1}}{2}, \mathrm{for\ m} > x \qquad (2)$$

$m > x$ means that all onsets are part of the priority set. Because the target is specified to be an onset, it follows that the target must be part of the priority set, and the no-priority set is therefore excluded from search. Because the priority set consist of x onsets, the expected number of comparisons required to find the target is simply (x+1)/2.

Equation 3 gives the expected number of comparisons *y* required to find the target when the target is a no-onset item and the number of priority tags is smaller than or equal to the number of onsets ($m \leq x$).

$$\mathrm{y(m; n, x)} = \mathrm{m} + \frac{\mathrm{n-m+1}}{2}, \mathrm{for\ m} \leq \mathrm{x} \qquad (3)$$

The priority set consists of *m* onsets, and because the target is specified to be a no-onset item, the entire priority set is searched first. This is represented by *m* in the left part of Equation 3. The right part of Equation 3 contains the number of comparisons required to find the target in the non-priority set (*n*-*m*+1)/2. Equation 3 can be reduced to

$$y(m; n, x) = m + \frac{n-m+1}{2}, \text{for } m \leq x \qquad (3a)$$

Finally, Equation 4 gives the expected number of comparisons *y* required to find the target when the target is an onset and the number of priority tags is greater than the number of onsets (*m* > *x*)

$$y(m; n, x) = \frac{m+n+1}{2}, \text{for } m \leq x \qquad (4)$$

The priority set consists of *x* onsets, and because the target is specified to be a no-onset item, the entire priority set is searched first. This is represented by *x* in the left part of Equation 4. The right part of Equation 4 contains the number of comparisons required to find the target in the non-priority set (*n*-*x*+1)/2. Equation 4 can be reduced to

$$y(m; n, x) = \frac{x+n+1}{2} for\ m > x \qquad (4a)$$

This model provides a framework making different predictions for the expected number of comparisons *y* as a function of *n* and *x* for various values for the parameter *m*. Figure 6.1 plots as an example (*n* = 8) the expected number of comparisons in six separate graphs for different number of priority tags (*m* = 0, 1, 2, 4, 6, and 8) as a function of number of onsets (*x* = 0 to 8), with separate lines for onset targets and no-onset targets. As can be seen in Figure 6.1, the zero-tag model

(m = 0) predicts that the onset has no effect at all, whereas the eight-tag model (m = 8) predicts a linear increase with each additional onset as well as a main effect of target type (i.e., onset targets require four comparisons less than no-onset targets). All other variations of m predict some form of interaction between target type and number of onsets.

In order to test this model a first experiment was conducted with display size fixed at eight and with target type (onset, no-onset) and number of onsets (x = 0, 1, 2, 4, 6, or 8) systematically varied. The idea was to see how well the empirical data fit with this model, which can take different values for number of priority tags (m = 0-8). The m value that provides the best fit between the model and the data would determine the number of onsets that could be prioritized in the task used in a given experiment.

Experiment 13

Experiment 13 used a visual search task in which participants were asked find ‘U’ or ‘H’ among other letters in the display. A placeholder search paradigm was used and the number of onsets was systematically varied from 0-8 while the overall display size was fixed at 8. Fixing the display size would be useful in interpreting RT changes as a function of number of onsets to changes in prioritization of onsets.

Method

Participants. Twenty two undergraduates (8 male, 14 female, mean age 19.4) from the University of Warwick participated in return for course credit. All of them reported normal or corrected to normal vision and were naïve to the purpose of the experiment.

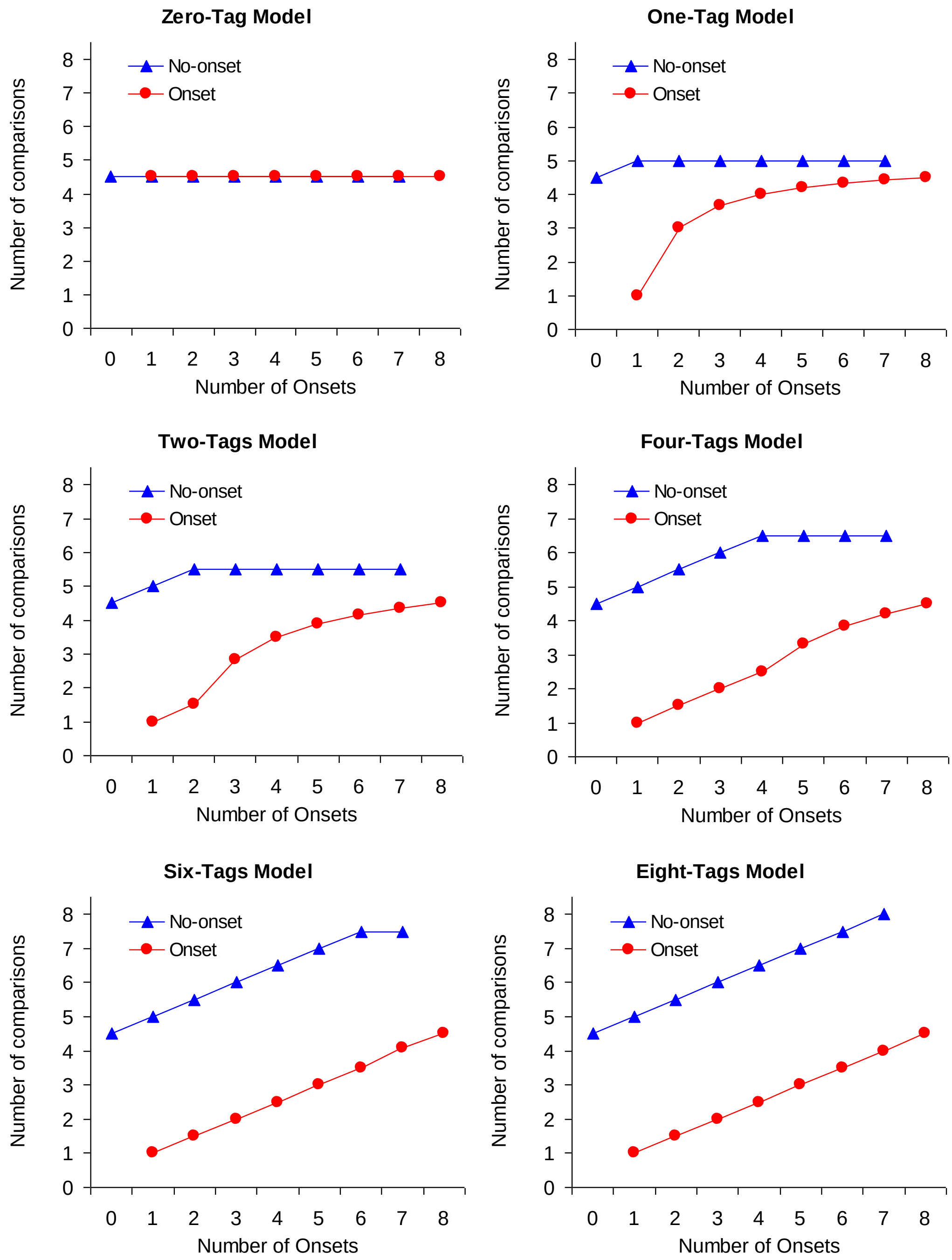

Figure 6.1. Expected number of comparisons *y* as a function of number of onsets *x* with separate lines for onset and no-onset targets. There are six graphs for variations of priority tags *m*.

Apparatus and Stimuli. The participants were seated in a dimly lit sound attenuated room in front of a 19” CRT monitor at a distance of approximately 57 cm. The monitor was driven at 100 Hz at a resolution of 1024 x 786 pixels. The experiment was controlled by an IBM-PC compatible computer using custom written software. Participants’ responses were recorded using left and right arrow keys on a standard keyboard. Stimuli consisted of a fixation cross, figure-8 placeholders, and letters, presented in grey drawn on a black background. The fixation cross was 0.6°x 0.6° visual angle and was presented at the centre of the screen. The figure-8 placeholders and letters subtended 1° by 2° and were made of seven line segments (length 1.0°, thickness 0.13°). The letters were ‘H’ and ‘U’ as targets and, ‘S’, ‘E’, 'F', 'O', 'C', 'P', and 'A' as distractors. The letters were made by removing the corresponding line segments from the figure-8. The stimuli were placed on the circumference of an imaginary circle (radius 12.5°) centred on fixation, such that the letters were equidistant from each other.

Procedure and Design. A trial started with the presentation of a preview display that consisted of a fixation cross and figure-8 placeholders. The number of placeholders varied among 8, 7, 6, 4, 2 or 0 so that the corresponding number of onsets in the display varied from 0, 1, 2, 4, 6, to 8 respectively. After 1000 ms the preview display was replaced by the search display which always contained eight letters. The no-onset letters were revealed by deleting the irrelevant line segments from the corresponding place-holders, whereas the onset letters appeared at previously unoccupied locations (see Figure 6.2). The target was equally likely to be an onset or a no-onset item (see Table 6.1).

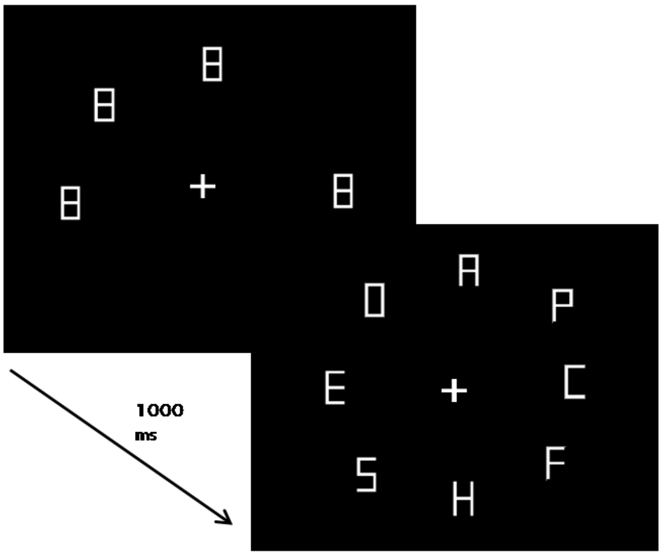

Figure 6.2. Example display in Experiment 13 with four onsets and four no-onset items. Display size was fixed at 8, but the number of onsets varied from 0, 1, 2, 4, 6, to 8.

Participants were asked to look for 'H' and 'U' targets among other distractor letters and to respond with the left and right arrow keys. Half of the participants used the left arrow for H and right arrow for U, and vice versa for the other half. They were instructed to respond to the target as fast as they could whilst trying not to make more than 5% errors. The search display stayed on until the participant responded or 10 seconds had elapsed. If no response was made within ten seconds, that trial was marked as an error. In the instance of wrong responses immediate feedback was given on the screen saying "error" and participants had to press the space bar to move on to the next trial. There was an inter trial interval of 1 second. For every number of onsets (x) condition, the target was an onset only on $1/x$ of the trials presenting that condition in order to ensure that the target type did not predict the target location. For example, when there was one onset, the target was a no-onset item in 7/8 of the trials and an onset in only 1/8 of the trials, but when there were four onsets the target was an onset or no-onset item in equal number of trials (see Table 6.1).

Each participant completed 20 practice trials followed by 400 experimental trials. The experimental trials were divided into 8 blocks of 50 trials each, with short enforced breaks between blocks. The experiment systematically varied three factors: target identity (H or U), target type (no-onset, onset), and number of onsets (0, 1, 2, 4, 6 or 8). All possible factor combinations were presented in random order. For the analysis, target identity was not further considered.

Results

RTs. Mean correct RTs were calculated for each target type and number of onset combination excluding 1.1% outliers (see Figure 6.3). A 2 x 4 Repeated Measures ANOVA with the factors target type (no-onset or onset) and number of onsets (1, 2, 4, or 6, excluding 0 and 8 onset in order to have a fully factorial design) were calculated. This showed a significant main effect of target type $F(1, 21) = 96.51$, $p < .001$: onset targets were on average found 113 ms faster than no-onset targets. The effect of number of onset was also significant $F(3, 63) = 6.79$, $p < .001$.

RTs increased on average by 46 ms from one to six onsets. Moreover, the interaction between target type and number of onsets was significant $F(3, 63) = 8.23$, $p < .001$. In order to further explore the interaction, two additional 1-way ANOVAs with the factor number of onsets showed no significant effect when the target was a no-onset item, F<1, but a highly significant effect when it was an onset, $F(4, 84) = 16.18$, $p < .001$, due to an RT increase of 103 ms from one onset to six onsets.

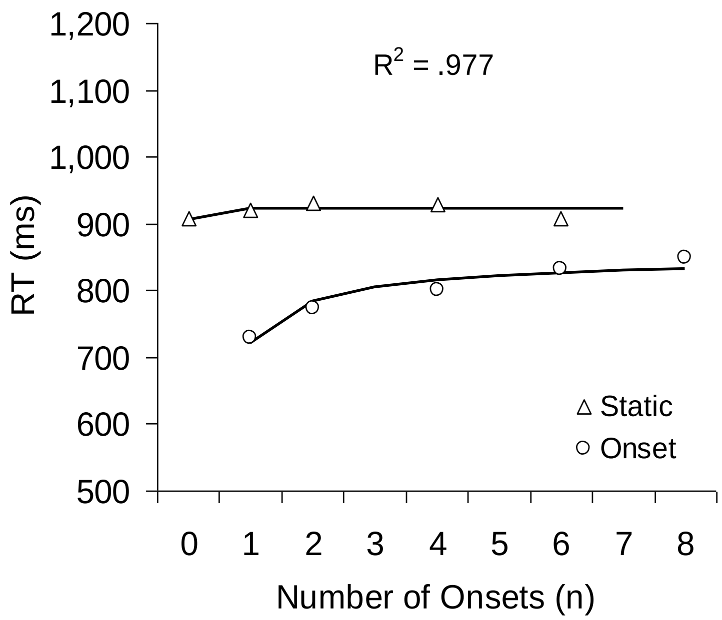

Figure 6.3. The markers show the mean correct RTs for static (no-onset) and onset targets in Experiment 13. The lines and R^2 show the result of a multiple regression analysis, predicting RT based on the 1-tag model, which provided the best fit.

Errors. Mean percentage errors were calculated separately for each participant and factor combination (see Table 6.1). Error rates were relatively low (on average 3.7%), suggesting that participants had no problem keeping errors below 5%. A 2 x 4 repeated measures ANOVA with the factors target type (no-onset, onset) and number of onsets (1, 2, 4, or 6 items) revealed a significant main effect for target type, $F(1, 21) = 6.03$, $p < .05$, due to the somewhat higher error rate with no-onset than with onset targets (4.4 vs. 2.9%, respectively). Although the two-way interaction between target type and number of onsets was not significant, $F < 1$, errors overall showed a very similar pattern to the RTs, suggesting that RTs were not confounded by speed-accuracy trade-offs.

Table 6.1.

Number of trials (N) and Errors (%) for target type and number of onsets in Experiment 13

		Target Type			
		No-Onset		Onset	
No. of onsets	Total no. of trials	N	Error (%)	N	Error (%)
0	20	20	4.1	0	-
1	160	140	4.3	20	2.4
2	80	60	4.6	20	2.2
4	40	20	4.8	20	2.8
6	80	20	4.3	60	3.0
8	20	0	-	20	3.9
Total (Mean)	400	260	(4.4)	140	(2.9)

Model fitting. A multiple regression analysis was used to determine the model parameters that make the best predictions for the RTs observed in Experiment 13. It is assumed that RTs depend on the expected number of comparisons as predicted by Equations 1-4 and for the different values of m as outlined in Figure 6.1. Consistent with the observation that RTs are in general faster with all-onsets displays than all no-onset displays (see Gibson, 1996), the factor target type is also included in the regression equation adding a constant to the formula when the target is a no-onset item.

$$RT(m) = a \cdot y(m; n, x) + b \cdot T + c \qquad (5)$$

The regression weight (*a*) is for the expected number of comparisons as predicted by the *m*- tag model, the regression weight (*b*) is for the target type (0=no-onset, 1=onset) and (*c*) is a constant representing all other processes involved in making a visuo-motor response (see Equations 1-4). The results of eight multiple regressions calculated separately for different values for number of priority tags (*m*= 1-8) are presented in Table 6.2. As can be seen in the last column, the 1-tag model provides the best fit (r^2=.977), with the goodness of fit continuously decreasing with increasing number of tags.

Table 6.2.

Summary of eight regression analyses predicting RT in Experiment 13 for Priority tag models (m), with the factors expected number of comparisons a, target type b, and the constant c.

M	a (SE)	b (SE)	c (SE)	R^2
0	- [a]	- [a]	- [a]	- [a]
1	31.6 (4.2)	-74.1 (10.3)	764 (21.7)	.977
2	27.7 (4.0)	-59.5 (12.4)	774 (21.8)	.974
3	26.7 (4.7)	-52.9 (16.0)	774 (26.8)	.963
4	23.6 (5.8)	-53.1 (21.3)	786 (33.8)	.939
5	21.4 (6.4)	-56.8 (24.6)	797 (38.3)	.920
6/7/8 [b]	18.8 (6.9)	-62.4 (27.5)	810 (41.7)	.900

Note. [a] The 0-priority tag model predicts no variation [b] The 6-, 7-, and 8-priority-tag models make the same prediction for this data set.

In order to compare the various tag-models, the same multiple regression analysis was calculated separately for each participant and each number of priority tags (*m*). A one-way ANOVA on these R^2 values with the factor tag, showed a significant effect, $F(5, 105) = 6.78$, $p < .001$. Posthoc LSD comparisons revealed that the difference between each level pair was significant ($p<.05$), except the difference between the 1-tag model and the 2-tag model ($p=.34$). This means that the 1- and 2-tag model provides a significantly better fit than the 3-8 tag models. Also, the 3-tag model provide a better fit than the 4-8 tag model, the 4-tag model than the 5-8 tag model, and the 5-tag than the 6-8 tag model.

Discussion

In Experiment 13, the effects of multiple onsets on attention capture were tested. Search displays with eight elements were used and the number of onsets was systematically varied. The results of a multiple regression analysis showed that the data was best supported by a model where only one onset is prioritized in search. Moreover, the pattern of RTs in Figure 6.2 shows the same numeric trend as the model in Figure 6.1 when only one onset is prioritised. For example, the RT increase for the onset target was largest when the number of onsets was increased from one to two. With every subsequent increase, the slope gradually decreases. This corresponds exactly to what is predicted by the 1-tag model. Moreover, the results showed no effect of the number of onsets when the target was a no-onset item, which corresponds well with the 0- or 1-tag model.

However, the present findings are in contrast to previous studies showing that more than one onset (up to 4) is automatically prioritized in search (Yantis & Johnson, 1990; Yantis & Jones, 1991). This could be due to some methodological differences between the present study and Yantis and colleagues' studies. For example, Yantis and colleagues always had in every trial an equal number of onset and no-onset items. That means paying attention to all onsets was “rewarded” in half the trials, whereas in the current study it was rewarded only in 35% of the trials. That is, there is more incentive in the present experiment to ignore onsets than in Yantis and colleagues’ studies. Another difference was that in the present study display size was fixed at eight and only the number of onsets was varied from trial to trial, whereas in Yantis and colleagues’ studies display size was varied to up to 16 items. It could be that their estimation of the deflection point in the RT slope is skewed by an overall flattening of the RT slope typically found at larger set sizes.

Strictly speaking, searching for a letter among other letters is only a moderately difficult task and after a certain point one would expect target identity to guide search rather than target type, which is irrelevant to the task. This is in line with purely bottom up models of attention capture which suggest that capture occurs because of increased salience of certain items at the first sweep of information through the brain (Theeuwes, 2010). However, after the initial feed forward sweep, re-entrant processes take over and the identity of the letters would be actively prioritized over its onset status. Thus, it would seem that the initial boost enjoyed by abrupt onsets is not sustained past the first location that is automatically attended to. Thus, the present experiment suggests that attention capture is better explained by a bottom up salience based model rather than an automatic priority tagging model.

Experiment 14

Experiment 14 tests whether the number of onsets that are prioritized becomes larger when onsets differed from the no-onset items in another easily distinguishable feature. That is, all onset letters appeared now in red whereas all no-onset letters stayed grey – the same colour as their corresponding placeholders. Having this additional feature could have three possible effects: First, because target type is irrelevant for the search task, the added colour might help to better ignore the irrelevant target type. In this case the best prediction would come from the 0-tag model. Second, the added colour could have the opposite effect, that is, it aids the automatic prioritization of onsets. In this case the best prediction would come from a multi-tag model (e.g., 3-8 tag models). Third, the added colour could have no effect on the search process. In this case the best prediction would come from the 1-tag model. In order to allow better estimates for the various tag models, two additional levels for number of onsets were added, that is, number of onsets was systematically varied from 0, 1, 2, 3, 4, 5, 6, to 8.

Method

Participants. Twelve students from the University of Warwick (3 male, 9 female mean age, 19.5 years) participated in return for course credit. None had participated in Experiment 13.

Apparatus, Stimuli, Procedure and Design. The apparatus and stimuli were the same as in Experiment 13, except that the all onset letters were presented in red. All aspects of the procedure and design were similar to that of Experiment 13, except that the conditions with 3 and 5 onsets were added, increasing the total number of trials in the experiment to 560 (see Table 6.3).

Results

RTs. Mean correct reaction times were calculated for each target type and number of onsets combination (See Figure 6.4).

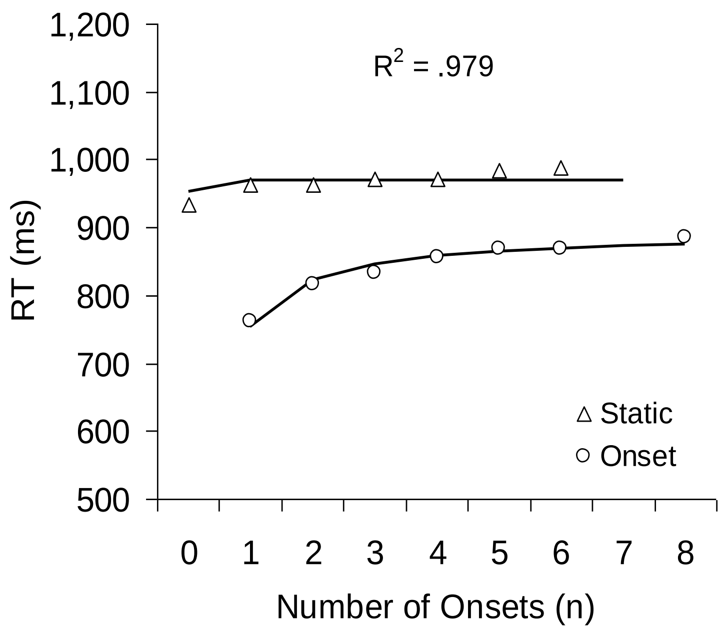

Figure 6.4. The markers show the mean correct RTs for static and onset targets in Experiment 14. The lines and R^2 show the best fit from a multiple regression analysis, predicting RT based on the 1-tag model.

A 2x6 Repeated Measures ANOVA with the factors target type (no-onset or onset) and number of onsets (1, 2, 3, 4, 5 or 6, excluding 0 and 8) showed a significant main effect of target type $F(1, 11) = 24.44$, $p < .001$: onset targets were found 139 ms faster than no-onset targets. The effect of the number of onsets was also significant $F(5, 55) = 3.68$, $p < .01$: On average RTs increased by 25 ms from one onset to six onsets. However, the interaction between target type and number of onsets did not reach significance $F(5, 55) = 1.39$, $p = .24$. The 1-way ANOVAs for no-onset targets with the factor number of onsets (now including 0 onset) showed no significant effect, F<1; however the ANOVAs for onset targets including 8 onsets showed a highly significant effect, $F(6, 66) = 4.99$, $p < .001$, due to an RT increase of 122 ms from 1-8 onsets.

Table 6.3.

Number of trials (N) and mean percentage errors (%) for each combination of target type and number of onsets in Experiment 14.

	Target Type			
	No-Onset		Onset	
Number of onsets	N	Error (%)	N	Error (%)
0	20	2.5	0	-
1	140	3.5	20	2.1
2	60	4.6	20	1.4
3	50	4.4	30	3.3
4	20	3.6	20	1.8
5	30	3.6	50	3.9
6	20	3.9	60	4.2
8	0	-	20	2.1
Total (Mean)	340	(3.7)	220	(2.7)

Errors. Mean percentage errors were calculated separately for each participant and factor combination (see Table 6.3). Error rates were relatively low (on average 3.2%), suggesting that participants had no problem keeping errors below 5%. A 2 x 6 repeated measures ANOVA with the factors target type (no-onset, onset) and number of onsets (1, 2, 3, 4, 5, or 6 items, excluding the 0 and 8 onset conditions) revealed only a marginally significant main effect for target type, $F(1, 11) = 4.78$, $p = .051$, due to the somewhat higher error rate with no-onset targets than with onset targets (3.7 vs. 2.7%, respectively). Again, there was no indication that RTs were confounded by speed-accuracy trade-offs.

Table 6.4.

Summary of eight regression analyses predicting RT in Experiment 14 for priority tag models (m), with the factors number of inspected items (a), onset target (b), and the constant c.

M	a (SE)	b (SE)	c (SE)	R^2
0	- [a]	- [a]	- [a]	- [a]
1	34.7 (3.8)	-77.9 (8.0)	797 (19.0)	.979
2	30.5 (3.2)	-58.4 (9.4)	806 (17.7)	.980
3	29.1 (3.4)	-45.8 (11.4)	805 (19.5)	.976
4	27.2 (3.9)	-41.2 (14.4)	810 (23.2)	.966
5	25.6 (4.1)	-41.1 (16.1)	816 (25.2)	.959
6/7/8 [b]	24.4 (4.2)	-42.8 (17.0)	821 (26.1)	.955

Note. [a] The 0-priority tag models predicts no variation [b] The 6-, 7-, and 8-priority-tag models make all the same prediction.

Model fitting. As for Experiment 13, a multiple regression analysis was used to determine the model parameters that make the best predictions for the RTs observed in Experiment 14 (see Equation 5). The results of eight multiple regression analyses calculated separately for different values for number of priority tags are presented in Table 6.4. As can be seen from the last column, the 1- and 2-tag model provides again the best fit ($R^2 = 0.979$ and $R^2 = 0.980$, respectively). However, the best fit values R^2 for each tag model was in a smaller range in this experiment (0.955 to 0.980) as compared to Experiment 13 (0.900 to 0.977). This was also confirmed in a one-way ANOVA on the individual R^2, which showed no significant effect for number of tags, $F < 1$. This means that in Experiment 14 all models provide a very good fit with R^2 values in the range of 0.96 to 0.98.

Discussion

Experiment 14 was conducted to test whether adding a distinctive feature to the onsets changes their attentional priority, either by strategies adopted by the participants or by changing their salience. As in Experiment 13, the best fit came from the 1- and 2-tag models. However, there was no significant difference in terms of best fits between the 1- and 2-tag models and the other multi-tag models. A possible reason for this smaller range of best fits might come from individual differences in the use of this colour feature. When looking at the individual distribution of best-fit R^2 values, in Experiment 13 the vast majority of participants (18 out of 22) seemed to use a 1- or 2-tag model. However, in Experiment 14 half of the participants (6 out of 12) seemed to use a multi-tag (3-8) model. This seems to indicate that when the onsets were coloured in red some of the participants were switching from a single-tag to a multi-tag strategy, where they pay particular attention to the coloured onset items. This would be a strategic top-down driven effect.

However, from Figure 6.4 it is clear that there is a numeric trend that it is more similar to the predictions for the model in which only one onset is prioritised. For example, it is clear that RT slope for onset targets is largest when the number of onsets increased from one to two. With every subsequent increase, the RT slope gradually decreases. Moreover, RT slope for no-onset target increases as the number of onsets increase from zero to one, but any subsequent increase in onsets does not affect the RT to find a no-onset target. If more onsets were prioritised in search, there would have been a definitive increase in search slopes when the target was a no-onset item.

However, it is important to note that 50% of the participants seemed to use a 1- or 2-tag model. This suggest that increasing the absolute salience of the onsets by drawing them in red did not affect capture for these participants because like target type, colour does not predict target location. Thus, participants do not have any incentive to attend to onset over no-onset items. That is, it seems that once attention is captured reflexively by an abrupt onset, participants are able to exert top-down control to focus on the task at hand and overcome subsequent capture. The finding that automatic capture is not sustained beyond one onset is, once again, not in line with the findings of Yantis and colleagues (Yantis & Johnson, 1990; Yantis & Jones, 1991).

Experiment 15

The results of Experiments 13 and 14 suggest that the majority of participants (70%) automatically prioritize and search only one or possibly two abrupt onsets in a display. However, it might be potentially possible to tag and search through more items with priority when it is demanded by the task. However this has not been tested previously in the context of attention capture with abrupt onsets. In the present experiment the task relevance of target type was manipulated such that participants always knew whether the target was an onset or a no-onset item. In order to allow participants to make best use of this information, target type was blocked such that in half of the experiment, the target was an onset whereas in the other half, it was a no-onset item.

Because participants always knew in advance set in which the target would appear, it was assumed that they would always prioritize the relevant target type. Hence Equations 1 and 2 are applied to both target types separately, because they assume that the target is always part of the priority set.

Method

Participants. Twelve students from the University of Warwick (3 male, mean age, 18.5 years) participated in return for course credit. None had participated in Experiment 13 or 14.

Apparatus, Stimuli, Procedure and Design. Apparatus, stimuli and procedure were the same as in Experiment 13. The design was very similar to that of Experiment 14, with the following differences. The target type was blocked with half the participants starting the condition where the target is an onset first and vice-versa for the other half. The number of onsets in each target type condition varied from 0 to 8. Because the target type was fixed, the number of trials in which the target was an onset and the trials in which it was a no-onset item was the same, giving a total of 512 trials (see Table 6.5)

Results

RTs. Mean correct reaction times were calculated for each target type and number of onset combination (see Figure 6.5).

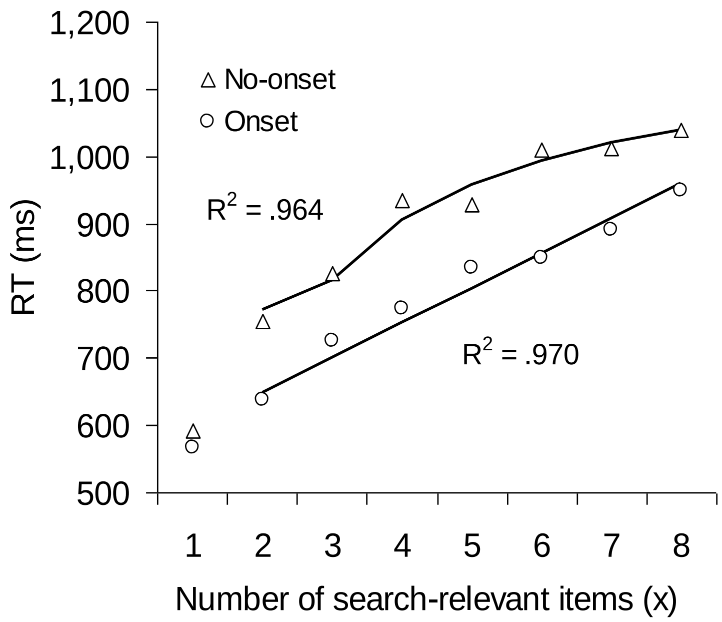

Figure 6.5. The markers show the mean correct RTs for static and onset targets in Experiment 15. The lines and corresponding R^2 show the result of two separate multiple regression analyses, predicting RT based on the 3-tag model for no-onset targets and the 8-tag model for the onset targets.

A 2x8 Repeated Measures ANOVA with the factors target type (no-onset or onset) and number of search-relevant items (1, 2, 3, 4, 5, 6, 7, or 8) showed a significant interaction, $F(7, 77) = 3.61$, $p < .01$. This interaction was due to the absence of a significant target type effect ($p = .12$) when there was only one search-relevant items (probably because the location of the target was 100% predicted by the one present or the one missing placeholder). This condition was excluded and a new 2x7 Repeated Measures ANOVA calculated, with the factors target type and number of search-relevant items (2-8). It showed a main effect of target type $F(1, 11) = 32.09$, $p < .001$: onset targets were found 108 ms faster than no-onset targets. The effect of number of search-relevant items was also significant $F(6, 66) = 54.70$, $p <$

.001: On average RTs increased by 298 ms from 2 search-relevant items to 8 search-relevant items. However, the interaction between target type and number of onsets did not reach significance $F(6, 66) = 1.61$, $p = .16$.

Table 6.5.
Number of trials (N) and mean percentage errors (%) for each combination of target type and number of onsets in Experiment 15.

	Target Type			
	No-Onset		Onset	
Number of search-relevant items	N	Error (%)	N	Error (%)
1	32	4.2	32	2.9
2	32	2.6	32	6.0
3	32	3.4	32	2.6
4	32	4.2	32	3.9
5	32	4.7	32	2.3
6	32	5.2	32	4.2
7	32	4.7	32	3.4
8	32	2.1	32	4.7
Total (Mean)	256	(3.9)	256	(3.8)

Errors. Mean percentage errors were calculated separately for each participant and factor combination (see Table 6.5). Error rates were relatively low (on average 3.8%), suggesting that participants had no problem keeping errors below 5%. A 2 x 8 repeated measures ANOVA with the factors target type and number of search-relevant items revealed no significant effects (all $p > .17$), indicating that RTs were confounded by speed-accuracy trade-offs.

Table 6.6.
<u>*Summary of eight regression analyses predicting RT in Experiment 15 separately for onset and no-onset targets for various priority tag models (m), with the factors number of inspected items (a), and the constant c.*</u>

M	a (SE)	c (SE)	R^2
No-Onset			
1	191.7 (21.3)	158 (86.6)	.941
2	95.8 (10.6)	589 (39.2)	.942
3	89.2 (7.7)	637 (26.5)	.964
4	87.6 (11.7)	655 (38.6)	.918
5	89.9 (12.1)	654 (38.9)	.917
6	91.5 (13.1)	653 (41.7)	.906
7/8	92.6 (13.1)	650 (41.4)	.909
Onset			
1	190 (23.2)	42 (93.9)	.931
2	95 (11.6)	471 (42.5)	.931
3	88 (8.4)	517 (29.0)	.957
4	89 (8.1)	528 (26.8)	.960
5	91 (8.6)	528 (27.8)	.957
6	94 (7.8)	523 (24.9)	.967
7/8	95 (7.5)	521 (23.9)	.970

Model fitting. As for Experiment 13 and 14, multiple regression analysis was used to determine the model parameters that make the best predictions for the RTs observed in Experiment 15 (see Equation 5). The results of 2 x 8 multiple regression analyses calculated separately for different values for number of priority tags and target type are presented in Table 6.5. Looking at the R^2, for no-onset targets the 3-tag model provides the best fit ($R^2 = 0.964$), whereas for onset targets the 8-tag model provides the best fit ($R^2 = 0.970$). This was also confirmed in a two separate one-way ANOVA on the individual R^2, of which both showed a significant effect for number of task-relevant items (both p <.01).

Discussion

The present experiment tested whether participants can selectively search through a subset of distractors when it is relevant to the search task. The results showed that RTs increased as the number of search relevant distractors increased while searching through both onset and static items. The results suggest that multiple items can be selectively searched through both onset and no-onset items with reasonable efficiency. Importantly, however there was a difference between onsets and no-onset items in the number of items that can be selected.

When the relevant set was made of onset items, the best fit was obtained in the 8 onset condition. Moreover, the fit seems to be equally good while searching through eight onsets and while searching through only one (range .931 to .970). This suggests that participants are able to search selectively through the onsets and ignore the no-onset items in conditions where the target is an onset item. One possible mechanism by which participants do this could be by actively inhibiting the location of the figure-8 placeholders by visual marking (Watson & Humphreys, 1997). In visual marking, participants successfully inhibit the location of known distractors (the preview) in a top-down manner so that they can selectively search through a new set of distractors. In spite of the methodological differences between the present study and studies using the placeholder search paradigm there are many reasons to believe why the data can be best explained by visual marking. For example, in visual marking, it is generally shown that a change to the preview display abolishes the marking (Watson, Braithwaite & Humphreys, 2008; Watson, & Humphreys, 2002).

In line with this, when the placeholders change to letters in the present study, it should have led to a failure in marking. However, successful inhibition could have been made possible in the present experiment due to various differences in design and stimuli relative to visual marking experiments. First, visual marking studies generally make use of targets and distractors that are defined by conjunction of two features, like colour and target identity/shape making it a difficult serial search where attentional guidance is difficult. However, in the present experiment, searching for U or H among other distractor letters should have been driven by their identity rather than feature conjunctions, making it relatively easier (also see Theeuwes, Kramer & Atchley, 1998, who showed that marking can occur even when all the items in the display are of the same colour and using multiple target items). Moreover, in visual marking studies, the items are presented in a random arrangement spread over the visual field, making it difficult to predict the location in which the new items are going to appear. However, in the present experiment the items were arranged in a circle making it easier to predict the locations of the onsets.

The present experiment also relates to discussions in the marking literature about the role of the abrupt onset of the search display in their prioritization. For example, Donk and Theeuwes (2003) found results that suggest that participants prioritize new items in spite of the absence of an incentive to prioritize. This finding indicates that search is overall faster when targets also happen to be new objects in the display. I this context, they speculated that multiple onsets might receive attentional priority in a bottom-up manner. However, this result could have been due to the intermixing of trials in which the target could be an old or a new item and does not necessarily reflect prioritization by multiple onsets. Moreover, in contrast to the onset best fit, the best fit (R^2 of .964) for finding the target among relevant no-onset items suggest that only up to 3 no-onset items could be selectively searched with priority. Because the number of items that are prioritised for each target type, it seems that participants may be adopting a different strategy to selectively search through the no-onset items as compared to the onset items.

Selective search through the no-onset items can be explained by the visual indexing theory, also called the FINST for 'fingers of instantiation' (Pylyshyn, 1989). According to FINST, it is possible to index or tag a small numbers of items in the visual field and these indexes can be used to track changes to these object. This indexing mechanism is controlled in a top-down manner and limited to about 4 items. The present results for the no-onset targets are consistent with this prediction of FINST. Moreover, it is assumed that this indexing is object-based, making it impossible to index empty locations, making FINST unsuitable while searching through a target among the onset items.

Note that it is difficult to determine whether or not onsets capture attention when the relevant set is made of no-onset items. Indeed, there is RT difference between onsets and no-onset items in all conditions, except when the number of relevant items was one. When it was one, there was only one relevant item in the display and participants could predict the location of the target from the information available from the placeholder display. A narrow attentional window adopted during search would have led to the absence of capture by onsets in that condition. However, overall, there is a difference in RT between the onset and the no-onset conditions. This difference in intercept has previously been noted by Gibson (1996a) who argued that faster RTs in displays with all onsets as compared to displays with all no-onsets results from a slower updating of the object files in the no-onset displays.

General Discussion

The present chapter describes three experiments testing the automatic nature of attention capture by multiple simultaneous abrupt onsets. Experiments 13 and 14 showed that when onsets are irrelevant to the task, only one onset captures attention. Experiment 14 further showed that this is the case even when the onsets are readily distinguishable from the no-onset items. Experiment 15 showed that when target type is relevant to the task, participants are able to search selectively through all the onsets and up to four no-onset items.

The findings of the present chapter, especially Experiment 13 and 14, are not in line with the priority tag model put forth by Yantis and Jones (1991). They proposed three possible models of capture, depending on whether 0, 1 or multiple onsets are prioritized. Of particular relevance are models 2 and 3 where either one or multiple onsets, respectively, are automatically prioritized.

Model 2 subsumes a saliency based mechanism of capture for onsets. According to this model, only one onset is prioritized during search and the RT to an onset target in a multiple onset display is mediated by the probability of the target being an onset. Such a model would speak strongly in favour of the role of salience in attention capture and would include abrupt onset in a category of features that capture attention when it is salient.

On the contrary, Model 3 assumes that all the onset items are tagged as high priority and searched before starting to search through the no-onset items. This model emphasizes the special status of abrupt onsets in attention capture because the priority tagging is assumed to be automatic and requires additional resources for maintenance. Thus, it is likely to be mediated by higher cognitive functions like memory rather than saliency maps. Yantis and colleagues' evidence in favour of a multiple priority tag model undermines the role of salience in attention capture by abrupt onsets. However, the findings of the present chapter prompt a re-evaluation of the role of salience or other low level transient features as a mediator of attention capture by abrupt onsets.

Chapter 7: General Discussion

Summary of the Empirical Chapters

This thesis presents a series of four studies investigating attention capture by dynamic stimuli in multi element displays. Most of the empirical tests are designed to test the theories of capture by motion onsets. Chapter 3 reports two experiments that examine the role of the refresh rate of motion in attention capture by motion onsets. Previous findings of attention capture by motion onsets (Abrams & Christ, 2003, 2005; Christ & Abrams, 2008; Christ et al., 2008; Franconeri & Simons, 2005) were followed up as it was suspected that capture in those studies were confounded by the refresh rate of the motion onset stimulus they used.

The findings of Chapter 3 indeed confirms this suspicion by showing that only the onset of jerky motion captured attention while the onset of smooth motion did not. Contrary to previous findings, the results suggest that motion onsets per se do not capture attention. Moreover, capture did not occur even with jerky motion for continuously moving items, suggesting that capture cannot be entirely attributed to transient signals that accompany jerky motion. It was concluded that theories of capture like the motion onset account, which subscribe to higher level mechanisms and evolutionary reasons, cannot explain these effects. However, explanations like the unique event account, which subscribe to low level factors like temporal uniqueness, are helpful at least in partially explaining the results.

Even though the findings from this study suggest an important role of low level motion changes in capture, it does not reveal the precise mechanisms governing attention capture. Neither does it explain why the onset of jerky - but not smooth motion captures attention. Hence, the next study was aimed at understanding how jerky motion onsets affect attentional prioritization. Following up from the bottom-up models of attention capture, it was hypothesized that motion as such might not be required at all and that simple flicker might capture attention.

Chapter 4 further explores the reasons for the differential effect of low refresh rate on attentional allocation to motion, in particular to motion onset. It was aimed to determine the precise reason for capture by jerky but not by smooth motion onset. In Experiment 5, it was hypothesized that the continuous luminance transients associated with jerky motion might capture attention. This was tested by looking at the effect of flicker on its own at various frequencies on attention capture. The flicker frequencies were comparable to the motion refresh rates used in the previous study. However, the results showed that flicker does not capture visual attention.

Next, study aimed to deconstruct the steps involved in the onset of jerky motion. In Experiment 6, the motion onset stimulus had smooth motion except for the first step, where the stimulus jumped as it would in jerky motion. Now, capture was found to vary as a function of jump size. That is, as the distance of the jump increases, the capture effect becomes stronger. Moreover, Experiment 7 and 8 showed that just a single jump without the subsequent motion (i.e., an abrupt displacement) is enough to capture attention. That is, an object that is displaced abruptly was shown to capture attention in spite of the absence of a higher level perception of change in location.

This effect is interesting when seen in conjunction with Experiment 9, in which the item is displaced as a figure-eight and then changes into a letter, as compared Experiment 8, in which it was displaced as a letter. The results show that the capture effect for abrupt displacement is now abolished, and the RTs are not different between static and displacement. It is argued that static letters become masked by the figure-eight place-holder, which delays the transmission of the letter signal for further processing. Thus, abrupt onsets and jerky motion onsets are attended first because they are both available for processing before the static item.

Taken together, the findings of Chapter 4 provide further support for the role of low level factors in attention capture. The results overall suggest that automatic attentional allocation is quite strongly affected by stimulus properties and low-level salience and visual quality. Thus, low level factors like masking can have a strong effect on the processing of visual signals.

In Chapter 5, a paradigm that was similar to those used in Chapters 3 and 4 was used, but with stimuli that moved back and forth instead of on a circular path. Capture was observed in this scenario, and remained unaffected by speed and smoothness of the direction change. That is, both fast and slow oscillations captured attention equally strongly and so did both gradual and abrupt direction changes. It was speculated that capture is probably mediated by a change in the direction of motion, rather than by a different type of motion. In further support of capture by direction change, Experiment 12 confirmed that the capture effect by direction change is also reflected in a difference in search slopes. The findings from this chapter also further support the conclusions in Chapters 3 and 4 that motion-onset per se does not capture attention.

Chapter 6 connects to the findings of chapters 3 and 4 by further testing the masking hypothesis for capture by abrupt onsets. Experiment 9 (chapter 4) had shown that capture by motion onset occurs because the static no-onset letters are all masked by the preceding figure-eight. Considering that the placeholder search paradigm is used to study capture by abrupt onsets, it is possible that the results of onset capture might have been confounded by masking. However, the role of masking has been previously tested and some evidence was found to support this hypothesis (see Gibson, 1996a. 1996b). However, there have been counter arguments, claiming that even when they are masked, onsets capture attention (Yantis & Jonides, 1996). Also, the new object account claims that more than one onset is prioritised in search by way of priority tagging. However, if capture is put down to masking, it is highly unlikely that more than one onset would receive an advantage. In case of masking, this would not be possible. In this context, the priority tag model of onset capture needs to be re-examined.

Three experiments were conducted using a similar visual search paradigm in order to examine the effects of multiple abrupt onsets on attention capture. To begin with, the number of onsets that are automatically prioritized was estimated. Previous studies have suggested that in visual search up to four onsets can be prioritized (Yantis & Jones, 1991; Yantis & Johnson, 1990). This finding favours the new-object account where items in a display are put in a priority queue and selectively searched through, rather than processing first the item that becomes available first. In the masking model, one onset might receive a priority due to better visual quality, but there would be no mechanism to keep track of which items in the display are onsets and which are not. Hence, after the first onset is processed, all other items in the display would be treated equally, ignoring their status as new objects.

Yantis and colleagues (Yantis & Johnson, 1990; Yantis & Jones, 1991) found that, even though the RT for an onset target increases linearly as the number of abrupt onsets increases, search rates remain unaffected for displays with more than four onsets. Thus, they concluded that during search up to four onsets are automatically prioritized and searched first before all the other items are searched.

In Experiment 13, a placeholder search paradigm was used and the number of abrupt onsets in the display was systematically varied from 0 to 8. The target being an onset or a no-onset was irrelevant to the search task and this was achieved by ensuring that an onset item in a display was no more likely to be the target than the no-onset item. The results suggest that automatic prioritization did not extend beyond one onset item. In Experiment 14, the onsets were made readily distinguishable from the no-onsets by presenting them in red. It has previously been shown that colour is a feature that can be ignored in search when it is task irrelevant. Thus providing the colour cue could have been helpful in overcoming the onset effect. However, the onset effect remained at only one onset item that becomes prioritised automatically, further supporting the masking account, which assumes that only one onset item could benefit from not being masked by the figure-eight placeholder (cf. Gibson, 1996a).

In Experiment 15, the target condition was blocked depending on whether the target is an onset or a no-onset. Participants were encouraged to actively search only through the relevant set while ignoring the distractors in the irrelevant set. The results suggest that participants could prioritise all the items in the relevant set when the target was an onset. However, when the target was a no-onset, participants could prioritize only up to four items in the relevant set. The results show that the visual system treats onsets and no-onsets differently and that attention is differently allocated. It is possible that this difference arises more from the difference in strategy used by the participants in accomplish the search task in these different scenarios.

In order to search through onsets, the best strategy would be to inhibit the placeholders, while in order to search through the no-onsets, the participant would have to inhibit empty location in which the onsets would be expected to appear, what would be quite difficult. Thus the amount of interference or changes from the inhibited set will explain which set would be easier to search through.

While top-down inhibition of the placeholders might be helpful in selectively searching through the onsets, FINST based indexing (Pylyshyn, 1989) aids searching through the no-onsets. That is, automatic prioritisation by abrupt onsets might not be mediated by priority tagging as was previously suggested. Yantis and colleagues' (Yantis & Jones, 1991; Yantis & Johnson, 1990) evidence in favour of a multiple priority tag model undermines the role of salience in attention capture by abrupt onsets. However, the findings of Chapter 6 prompt a re-evaluation of the role of salience or other low level transient features as a mediator of attention capture by abrupt onsets. The results also reinforce the findings from the previous chapters that low-level salience is more important for capture than higher level perceptual events. Overall, the thesis endorses a bottom-up rather than top-down model to explain attention capture.

Theories of Capture

Behavioural-urgency and Animacy

In order to draw a conclusion, it would be important to revisit the theories of capture and to examine how much the findings from the present thesis have contributed to these theories. The most popular accounts of capture by motion onsets are the animacy account by Abrams and colleagues (Abrams & Christ, 2003; Pratt et al., 2010) and the behavioural urgency hypothesis by Franconeri and Simons (2005). The essence of both of these accounts is quite similar. While the animacy theories propose that the onset of motion is a feature that can be used to differentiate between animate and inanimate objects, the behavioural urgency hypothesis claims that an object that begins to move is behaviourally highly relevant.

Using evolutionary arguments, both theories concede that animacy and behavioural urgency captures attention. In some sense the behavioural urgency hypothesis can also account for explanations of capture as given by the animacy theories. For example, it can be argued that it is important to quickly detect the presence of animate objects in the surroundings as this information could be coupled with a quick behavioural response. That is, the animate object might be a predator, in which case survival depends on quick responses; or it might be a prey in which case also, the speed of response is critical for survival. Hence it seems that at least a behavioural level both the theories can be treated similarly.

Thus, in essence both these theories are evolutionary explanations of attention capture. In this context, the theory refers to physiologically determined automatic responses that have come about as a result of adaptive processes over generations. However, the explanations given for the animacy account does not seem to correspond too well with this reasoning. For example, according to Abrams and Christ (2006), attention capture is not caused by lower-level changes in luminance-defined contours, but instead by higher-level changes in the perceived location of the object. That is, this explanation emphasize the role of conscious perception of a change in the location of an object in automatic attentional selection and not unconscious, luminance changes. This definition is problematic in a framework that sees attentional selection as a precursor to conscious perception. Nevertheless, the present study has clearly demonstrated that such a change in the perceived location is not sufficient for attention capture, because capture did not occur with smooth motion, despite the evident change in the perceived location of the object. Thus, the present study allows for a new interpretation of Abrams and Christ's (2003) findings, where lower-level changes play an important role in attentional prioritization.

Unique Event Account

Chapters 3 and 4 tests to see whether the Unique Event Account (von Mühlenen et al., 2005) is a better explanation of the capture effect than the evolutionary theories. According to the Unique Event Account, attention capture is mediated by the overall perceptual noise in the display during the presentation of the motion onset. That is when motion begins at a time when no other changes occur in the display, it captures attention. This account essentially endorses a bottom up view of attentional control to the extent that it puts down capture to the availability of a strong transient signal that is free from other competing signals. In that sense, Unique

Event Account only as much as lay down certain conditions required for strong capture. This is also in line with the broader view that attention capture has a strong bottom-up component that is primarily saliency driven (e.g., Theeuwes, 2010). It remains an open question whether the temporal uniqueness of an event, as described by the UE account, leads to an increase in the saliency of that event or whether it leads to an increase in the priority of that event at a later processing stage. The findings from the present thesis go beyond the Unique Event Account by providing an explanation of capture by motion onset.

New Object Account

The new object account (Hillstrom & Yantis, 1994) is one of the most debated and tested theories of capture by abrupt onsets. Abrupt onsets have been shown to capture attention consistently and across different paradigms. Most studies use displays that are made of figure-eight placeholders which then change to letters simultaneously with the presentation of the abrupt onset. That is, the final display consists of objects whose history classifies them as onsets and no-onsets. It was argued that abrupt onsets capture attention because they are new in the visual scene and is automatically prioritized. Some studies looked at the role of differences in local luminance between onsets and no-onsets as reasons for capture. Even when such differences were controlled for, these studies failed to completely abolish the capture effects by abrupt onsets. Nevertheless, it was shown that when local luminance differences between onsets and no-onsets were matched, it reduced the capture effect significantly, but did not abolish it (cf. Miller, 1989).

This and other evidence directly testing the new object hypothesis further supports the new object account (Yeshurun et al., 2009; Wong, Petersen & Hillstrom, 2007; Rauschenberger & Yantis, 2001). However, it may seem that the results from these studies might be confounded by various factors. For example, Hillstrom and Yantis (1994, Experiment 1) used different types of motion and found the lowest slopes for back and forth oscillation. In their Experiment 2, they used the same type of motion at a low refresh rate (10 Hz) and this defined the appearance of a new object. Thus, in line with the findings from previous chapters, it could be the onset of jerky motion that captured attention, rather than the appearance of a new object.

In other studies, there are confounds with regard to the size of the new object. For example, in Rauschenberger and Yantis, (2001), the size of the subjective square is twice as large as that of the other display items. Even though this square was not always the target, the conclusion cannot be accepted as long as the interaction effects between size and newness is verified. The same applies to Yeshurun et al. (2005), where the capture effect of the perceptual object can perhaps be attributed to the fact that the object was at least 4 times larger than the distractors. Thus it may seem that the evidence favouring the new object account is not as strong as previously thought. Hence, it also seems worthwhile to revisit the alternate explanations of capture by onsets.

As noted previously, one well fitting explanation of the onset effect is the masking hypothesis, according to which the onsets are attended to or processed first because it is available to the visual system earlier than the no-onsets (Gibson, 1996a, 1996b). In other words, the figure-eight might render the no-onsets difficult to encode and thus slowing their processing down. Gibson (1996a) tested this hypothesis by testing how varying the luminance of the mask changes the overall search rates. He used three different placeholder conditions – bright, dim and onset (no placeholder). In the bright conditions, the luminance of the placeholders was the same as that of the letter, while in the dim condition the placeholders were dimmer than the letters. In the onset condition, there were no placeholders, meaning that all the elements had an abrupt onset. The final search displays were identical in all the three conditions.

The results showed that participants were fastest in the onset condition, followed by dim placeholder condition. The slowest RTs were found in the bright condition. In a second experiment, bright and dim placeholders were combined with either an onset or no-onset target. In the dim placeholder condition in which the placeholders for the no-onset stimuli were dimmer than the letters, onsets did not capture attention. However, strong capture was observed in conditions in which the placeholders were brighter than the letters. The results overall suggests that attention was automatically guided to the stimulus that had a better visual quality and that this effect was stronger in conditions in which masking was stronger in the distractors.

However, Yantis and Jonides (1996) reinterpreted the advantage of an all onset display in terms of a faster processing associated with capture by onsets. They argued that the pattern of results found in Gibson's (1996a) study is the opposite of what is expected based on the general principles of forward-masking. They also argue against masking as the critical factor in Gibson's findings based on their previous research where they test for masking by placeholders. For example, Yantis and Jonides (1984) conducted a control experiment in which detection times were measured separately for onset and no-onset letters. They showed that there is no difference in RT between two stimuli which were attended to, irrespective of whether or not a placeholder preceded them. However, later studies have shown that there are other forms of masking that changes based on attentional control settings (Enns & Di Lollo, 1997). For example, in object substitution masking, four dots that were placed around a target object were shown to act as a mask when attention was not focused on the object. In the present thesis too, the critical factor could be whether attention is focused on a search item or not.

Yantis and colleagues' (Yantis & Jones, 1991; Yantis & Johnson, 1990) evidence in favour of a multiple priority tag model undermines the role of salience in attention capture by abrupt onsets. However, the findings of the present chapter prompt a re-evaluation of the role of salience or other low level transient features as a mediator of attention capture by abrupt onsets. According to a masking explanation, it seems not very plausible that in a display containing multiple onsets, more than one onset will be prioritized for search as the masking effects are transient and short-term.

Conclusions

In general, the findings of the present thesis speak in favour of a strong role for low level feature changes and properties in attention capture. For example, the results from Chapters 4 and 6 suggest that attention capture by motion onsets and abrupt onsets are strongly mediated by low level factors such as masking (respectively the absence of masking). Further evidence against the involvement of higher level perception in attention capture comes from Chapter 2, which shows that a higher-level change in object status from stationary to moving is not sufficient for capture. The results also speak against the view that capture results from an evolutionary requirement to prioritize animate objects. It can be explained by very simple low level factors, such as temporal uniqueness and better visual quality.

The overall findings call for a re-conceptualisation of capture by dynamic events. In the literature on attention capture by static features and singletons, findings are often explained in terms of low level salience computations. However, research on attention capture by dynamic events predominantly subscribes to explanations that are driven by higher level factors. For example, attention capture by motion onsets is often explained as directly resulting from an evolutionary need for the visual system to prioritise animate objects over inanimate objects. Or it is explained as a way to respond in a more efficient manner to events that are behaviourally urgent. However compelling and intuitively convincing these accounts may seem, they are often not more than generic explanations that do little to advance our understanding of the processes involved in attentional selection and prioritisation.

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