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Task difficulty determines the amount of attentional
resources devoted to visual processing

Lyne Racette

Master's thesis
Carleton University
September 1997

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acceptance of the thesis

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resources devoted to visual processing**
submitted by **Lyne Racette, B.A.**
in partial fulfillment of the requirements for
the degree of Master of Arts

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ABSTRACT

The feature integration theory of attention postulates that feature perception is governed by preattentive mechanisms, while feature integration is governed by attention. I suggest that attention may be required to process all visual information, but to a different extent depending upon task difficulty. Attention would be distributed along a continuum rather than being a dichotomous process. Two experiments were conducted using a visual search paradigm: one with feature perception, the other with feature integration. In each experiment, two conditions were run: one easy and one difficult. Task difficulty was manipulated by varying the target-distractor discriminability. Results show that searches consistent with both parallel and serial processing can be obtained for both feature perception and feature integration. The results are interpreted to show that attentional allocation is dependent upon task difficulty. Attention is argued to be a process distributed along a continuum rather than being a dichotomous process.

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The visual system is extremely proficient, allowing us to perform complex tasks in a reflexive manner. We do not, for example, devote much thought to recognizing familiar objects, navigating in our environment, or pouring a cup of tea. Though very complex, we are able to perform these tasks without a conscious appreciation of the detailed processing which must be entailed. The visual attentional system contributes to this high level of performance by enhancing visual processing.

Multiple brain areas contribute to the attentional system (Colby, 1991). Attentional processing does not occur at a single specific location within the brain, however activation of the entire brain is not required for attentional processing to occur (Mesulam, 1981, 1990; Posner & Petersen, 1990). The complexity of the attentional network can account for the variety of attentional deficits reported in the literature. For example, Posner, Rafal, Choate, and Vaughan (1985) found a deficit in shifting attention to cued locations in patients with progressive supranuclear palsy (PSP). PSP is a degenerative disease which affects midbrain structures including the superior colliculus which is thought to play a role in attentional processing. Evidence from studies on patients with parietal lobe lesions shows a deficit in perceiving objects even in those areas of their contralesional field (contralateral to the lesion) where no sensory perceptual defects are observed. These deficits can take two forms: neglect and extinction. Patients with neglect are unaware of stimuli presented in their contralesional

visual field. It is thought, however, that they retain some primitive ability to process these stimuli (they can for example reach out and grab an object if prompted to do so). Extinction is a similar condition with the exception that patients can perceive a stimulus in the contralesional field when no other competing stimulus is presented in the ipsilesional field. In both neglect and extinction, stimuli presented in the contralesional visual field are processed to some extent, but attention is deficient.

The attentional system therefore contributes to visual perception in that it allows for efficient use of the available visual information. The different brain areas involved in attentional network make different contributions to visual processing. Primitive structures, such as the midbrain, are involved in low level functions such as eye movement control and orienting towards an exogenous cue. Cortical structures may control higher level functions such as the voluntary processing of specific visual stimuli. There is evidence, however, that the primitive and cortical attentional structures interact when processing visual information (Eason, Harter, and White, 1969; Zackon, Casson, Stelmach, Faubert, & Racette, 1997).

Structures which emerged at different times in neural evolution contribute to the attentional system. Given this view of attention, one can assume that the attentional network influences all stages of processing (both simple and complex).

The goal of the present research is 1) to provide some evidence that attention may be a process distributed along a continuum, rather than a dichotomous one; and 2) to show that, unlike what was suggested by the feature integration theory (Treisman & Gelade, 1980), the role of attention is not solely to integrate features, but rather to allocate visual processing resources, such that difficult tasks are allocated more resources while easy tasks are allocated less resources.

The role of attention in normal visual processing

Posner (1995) defined three roles played by attention in normal visual processing: maintaining general arousal, orienting to sensory stimuli, and prioritizing motor actions, objects of consciousness and memories. In terms of maintaining general arousal, attention ensures that visual scenes are always processed, at least to some extent. All locations of the visual field should be monitored at all times, such that any important event can be detected and processed. This attentional function maintains the visual system in a state of alertness necessary for further processing to occur. Eason et al. (1969) studied the combined effects of general arousal and focused attention on evoked cortical potentials. They found a main effect for focused attention, where attended stimuli resulted in stronger evoked potentials. They also found a weaker but significant main effect for arousal: by varying the state of arousal (through threat of shocks), greater evoked potentials and faster response latencies were found for high

arousal conditions than for low arousal conditions. A significant interaction was also found between arousal and focused attention. When a stimulus was attended, the amplitude of the potential it evoked was a direct function of the arousal level. When a stimulus was unattended, the level of arousal had little effect on the magnitude of the evoked potential. Focused attention and general arousal therefore interact to determine the net change in the amplitude of evoked potentials while performing an attention-demanding task.

Attention is also thought to act as an orienting mechanism. Since the visual system is thought to be a limited capacity processor, there is a need to select the most relevant stimuli which will receive further processing. Attention orients the visual system to the most relevant stimuli. It acts as a filter, or as a gating mechanism, which prevents irrelevant, or less important stimuli from being processed.

Finally, attention can be defined as a prioritizing device: motor reactions can be rank-ordered in view of the object of attention. For example, a saccade is usually initiated when a new stimulus is presented (orienting), but when attention is engaged by another stimulus, the saccade can be suppressed. Attention therefore gives priority to specific motor responses and it is thought to also give priority to objects of consciousness and to memories (Allport, 1980). Yantis and Jonides (1990) also suggest that attention acts as a prioritizing device. They believe that abrupt onsets within the visual field create a "priority signal". This

signal enters a queue: each signal in the queue is processed in order of priority.

When attention is diffuse, abrupt onsets have the highest priority; but when attention is focused, the focused location has the highest priority and is processed before anything else (including the abrupt onset).

In sum, attention plays a role in arousal, in orienting to sensory stimuli, and in prioritizing either motor responses, consciousness, or memories. The present study will focus on the impact attention has on visual processing in terms of orienting to visual stimuli. It will also focus on the prioritizing role played by attention in visual processing.

Attentional cueing (exogenous versus endogenous)

Attention has been defined thus far in terms of the effect it has on visual processing, but one could also define attention in terms of the mechanisms by which it is guided. In some cases attention is attracted to a location in space because of the sudden onset or offset of a stimulus at a specific location in space. In other cases however, attention is directed to a particular location because of the relevance of that location to the task at hand.

The sudden onset or offset of a highly salient stimulus at a given spatial location within the visual field can attract attention to that location, and this is referred to as exogenous cueing. This type of attention is believed to be stimulus-driven and is thought to operate in a bottom-up fashion. Novel events should

receive some visual processing as they may contain important information. For example, an animal has much to gain by processing the sudden appearance of its predator. Exogenous shifts of attention can occur even in the absence of eye movements. Robinson and Kertzman (1995) showed that neurons in the superior colliculus may be responsible for exogenous shifts of attention when no eye movements occur. In the literature, pop-out targets in the visual search paradigm (Treisman & Gelade, 1980) illustrate this exogenous attentional shift. When a target differs from the surrounding distractor items by a single feature (i.e. a yellow triangle among red triangles) it appears to "pop-out" from the display. Because the target differs from the distractor items, it grabs attention and is processed rapidly and in parallel.

In addition to being drawn to a specific location due to any sudden change occurring at that location (exogenous cue), attention can also be voluntarily directed to a location. This type of attention is referred as endogenous. Orienting attention to endogenous cues allows for the processing of stimuli which are potentially less salient but which may be important to the task at hand. When a particular behavior requires that attention be given to a stimulus which is important to the successful accomplishment of that behavior, it is said that attention is task-driven and governed by a top-down process. The study of attention therefore requires that importance be given to both the perceptual and cognitive aspects of any task. In the present study, the visual search paradigm will

be used, and the stimulus configurations modified such that the target will pop-out in some conditions (exogenous cueing), and will be actively searched for in other conditions (endogenous cueing).

Models of attentional functioning

Some models of attentional processing (e.g. the spotlight and zoom-lens models) hold that focusing attention enhances visual processing. This enhancement can be due to the increase in processing resources devoted to the attended stimulus, or to the reduction in processing resources given to the unattended stimuli. The enhanced processing of attended stimuli is thought to result from the amplification of the activity (i.e. increased firing rate) of many brain areas. The decrease in processing resources can be attributed to the suppression of the activity of some brain areas.

In reality, however, it is possible that both phenomena (enhancement of attended stimuli and inhibition of unattended stimuli) occur simultaneously. Moran and Desimone (1985) found amplified magnitude of cellular recordings for attended stimuli in awake monkeys; however, cells in area V4 simultaneously showed suppressed response to the unattended stimulus which was optimal for initiating cell firing. Another example of amplification associated with suppression is given by Chelazzi, Miller, Duncan, and Desimone (1993). They showed that a given stimulus could either enhance the firing rate of a specific cell

(when the stimulus was attended) or suppress that cell's firing rate when the stimulus was unattended.

Posner and Dehaene (1994) proposed an attentional network model which incorporates how inhibition and enhancement can work together. They suggest that this processing asymmetry can occur because of the suppression of unattended stimuli at early processing stages, and the amplification of the attended stimuli later on in the processing stream. Their suggestion is that the neurons in areas such as V1 fire strongly in response to visual stimuli, regardless of whether the stimuli are attended or unattended. Therefore, at early stages of processing, attention can control processing by selectively suppressing the automatic neuronal activity. At later stages within the processing stream, attention can enhance the response of cells in extra-striate structures such as area V4 for example. Even further up the cortical hierarchy, some cells are activated only when specific tasks are accomplished, and never fire in passive situations: for these cells, attention appears to be required for firing to occur. This attentional network accounts for both enhancement and inhibition, and suggests that attention is distributed along a continuum.

This view proposed by Posner and Dehaene (1994) implies that attention can have an impact at all stages of visual processing. It is a well accepted fact that attention influences complex visual processing; however, there is an ongoing debate as to whether attention impacts on early visual processing. Some

researchers hold that there are two processing channels: one preattentive, the other attentive. Braun and Sagi (1991), for example, argue in favor of two distinct processing channels. In their study, participants had to either discriminate between two letters, or detect a feature gradient (Gabor patch), either centrally or peripherally. In some conditions, participants had to perform only one task, while on other conditions they had to perform a dual-task. They found that when participants had to perform a single task, performance was equally good for letter discrimination and feature gradient detection. However, when participants had to perform both tasks, they found that identifying letters as a secondary task showed serious impairment. This was not the case for detecting a feature gradient. These results were interpreted as showing that the detection of a feature gradient does not rely (or relies only marginally) on focal attentional processing. This study therefore gives support to the view that there may be two processing channels. The first, independent from attention, could be responsible for the processing of low-level stimuli such as feature gradients. The second, would require attention to process higher-level stimuli.

Treisman and Gelade (1980) also argue in favor of a dichotomous view, where some tasks can be performed preattentively while others require attention. They suggest that feature perception tasks (where a target is defined by a single feature) are performed at a preattentive level, while feature integration tasks (where a target is defined by a conjunction of two or more features) require

attentional processing to be performed.

Mechanisms of attentional enhancement

Various models have been proposed to account for the beneficial effects of attention on visual processing. The zoom-lens model (Eriksen & St. James, 1986; Eriksen & Yeh, 1985) proposes that the area over which attention is extended is variable. When the attended area is small, attention is highly beneficial to visual processing. When the attended area is large, the benefits of attention are smaller. There is a trade-off between the attentional area and the attentional effectiveness. This model then implies that a fixed amount of attention is distributed across a specific region: the smaller the region, the more highly "concentrated" attention is. Another attentional model put forth by LaBerge and Brown (1989) is referred to as the gradient model. Here attention is thought to emerge at specific locations within the visual field, thus creating an attentional gradient. Processing resources are thought to be distributed across the visual field according to the attentional gradient. The attentional gradient is continuously modified depending on the allocation of resources.

Attention has been compared to a spotlight which is being moved across the visual field (LaBerge, 1983). Posner, Snyder, and Davidson (1980) also compared attention to a spotlight and suggested that visual processing would be enhanced within the spotlight area and inhibited outside the spotlight area.

Maximal visual processing would occur in the centre of the spotlight, slowly decreasing as one moved away from the centre. Based on the spotlight analogy, Posner et al. proposed a three-stage model of attention where one engages a visual stimulus, disengages from it and shifts attention onto a new stimulus.

In the models described above, attention is thought to enhance visual processing by creating a gradient of resources within a specific area. Processing is therefore heightened at the attended locations. A different way to conceptualize how attention enhances visual processing was proposed by Treisman and Gelade (1980). They proposed the feature integration theory to explain the nature of the attentional facilitation on visual processing. Objects are composed of numerous features, such as size, color, shape and orientation. Each object can be defined as the sum of its features. Subjectively, we do not perceive individual features, but rather the whole of the object defined by the features. The feature integration theory suggests that individual features can be processed preattentively, but that attention is required to integrate features.

One of the paradigms used by Treisman and Gelade (1980) to study attention was visual search, where participants are asked to detect a target item embedded in an array of distractor items (the target is present on some trials and absent on others). When the target is defined by a single feature (i.e. search for a red circle among green circles), it appears to pop-out from the display, regardless of the number of distractor items present. The perception is such that the target

distinguishes itself from the distractor items and captures attention. In such a case, when the number of distractor items present in the display is plotted as a function of target detection latency, the line has a slope near or equal to zero (< 5 or 6 ms per item) (Treisman & Souther, 1985). In other words, a flat search function is obtained, showing that increasing display size does not result in increased target detection latencies. The search for the target therefore appears to occur in parallel, and according to Treisman and Gelade, at a preattentive level.

When the target is defined by a conjunction of two or more features (i.e. search for red circle among red squares and green circles), the search is thought to be serial. Target detection latencies increase as the number of distractor items increase (the search slope is no longer flat). The proposed explanation for these increased latencies is that the integration of the features of the target into a single stimulus requires attention. Therefore, the target no longer pops-out from the display and the attentional focus must be shifted serially across the visual field until the target is found. Each location is processed serially either until the target is detected (self-terminating search), or until all items have been processed (exhaustive search). Serial searches are assumed to be self-terminating when the slope for the target absent condition is approximately twice as steep as the slope for the target present condition (Sternberg, 1966).

The notion that each location is processed serially is based on the fact that the features of each specific item share the same location in space. For example, a

red circle is composed of two features (red from the color map, and circle from the shape map), and spatial location is coded in each feature map. When searching for a red circle, a good strategy would be to scan each potential location until the two features (red and circle) are found at one specific location. The information from that location is then integrated, and a temporary object representation is made. This representation is then compared with established descriptions of objects. According to Treisman and Gelade (1980), once a stimulus has been recognized, attention can be shifted to a different location. Therefore, when a stimulus is defined by a conjunction of features, it is searched for serially and the slope relating detection latencies to display size is greater than zero (not flat).

In sum, the feature integration theory establishes a dichotomy between preattentive and attentive processes. It postulates that attention is required to integrate the features present at any one location, as searches consistent with serial processing are found when the target is defined by a conjunction of two or more features. When the target is defined by a single feature, searches consistent with parallel processing are obtained, suggesting preattentive processing within the feature integration theory.

The approaches of Posner et al. (1980) and of Treisman and Gelade (1980) towards attentional processing are fundamentally different; Posner et al. are concerned with the movement of attention across the visual field and suggest a three-stage model where attention is thought to engage a stimulus, disengage from

that stimulus and shift onto a new stimulus. Treisman and Gelade are not mainly concerned with the pattern of movement of attention, but rather try to explain how attention enhances visual processing once attention is engaged onto a stimulus. A comparison of these two conceptualizations of attention is therefore difficult.

What is readily apparent, however, is that both models are based on a dichotomy between preattentive and attentive processing. In Posner's view, only stimuli located within the attentional spotlight benefit from enhanced processing.

Unattended stimuli can be processed, but without the involvement of attention (preattentively). Likewise in Treisman and Gelade's view, feature perception is performed without attention while feature integration benefits from attentional processing. Visual processing at the preattentive level is thought to be carried out by simpler mechanisms such as perceptual segregation. Therefore, both Posner et al. and Treisman and Gelade establish a dichotomy between preattentive and attentive processes.

Continuum vs. Dichotomy

There are problems associated with this dichotomous view of attention where, according to Treisman and Gelade (1980), the type of search obtained is feature dependent. Some researchers have reported searches consistent with parallel processing for feature integration tasks. For example, Nakayama and Silverman (1986a) found flat search functions relating detection latency to display

size for feature integration of binocular disparity and both color and motion in a visual search paradigm. Search functions consistent with parallel processing were also found for feature integration of color and motion, and for all possible combinations of binocular disparity, spatial frequency, size, color, and direction of contrast (Nakayama & Silverman, 1986b). These search functions which are consistent with parallel processing were found using highly discriminable stimuli. For example, McLeod, Driver and Crisp (1988) reported flat search slopes for the integration of shape and motion direction. Steinman (1987) reports similar results when integrating binocular disparity and orientation or Vernier offsets. Searches consistent with parallel processing were also reported for the integration of contrast polarity (black and white contrasts) and shape ("X" and "O") (Theeuwes & Kooi, 1994). When participants receive high levels of training on a specific task, Steinman reports parallel searches for integration of Vernier offsets and both orientation and lateral separation. Furthermore, Wolfe, Cave, and Franzel (1989) found flat slopes for the integration of highly discriminable features for orientation, shape and color. Finally Pashler (1987) suggested that for display sizes smaller than eight items, searches may be performed in parallel even for feature integration tasks.

Results consistent with serial processing were obtained by Laarni, Näsänen, Rovamo, and Saarinen (1996) for a feature perception task. The target (Gabor patch) differed by 90° in orientation from the distractor items; contrast

threshold served as the dependent variable. They found that the contrast threshold almost doubled as the number of possible target locations increased from one to eight. This effect of display size which is consistent with serial processing was found for a feature perception task.

Furthermore, there is a large body of evidence in the literature supporting the idea that the type of search obtained (consistent either with parallel or serial processing) may not be solely feature dependent (feature perception or integration). Researchers have manipulated various factors (other than the type of features), and have obtained results inconsistent with the feature integration theory. All these factors, although different from one another, are similar in that their effect is to vary the difficulty of the task at hand.

One way to manipulate task difficulty is to vary the structural complexity of the stimuli. For example, Hogeboom and van Leeuwen (1997), using a matching task rather than a visual search task, report that searches consistent with serial processing are more likely to be obtained when stimuli have structural complexity and for those participants who prefer accuracy over speed in their performance. In their experiments, searches consistent with parallel processing occurred for simpler targets and for those participants who opted to respond rapidly. The search slope was apparently determined by the response strategy adopted by the participants and by the structural complexity of the stimuli: not by the number of features contained within the stimuli.

Another way to manipulate task difficulty, is to use different tasks.

Saarinen (1996a) found that target discrimination is conducted in parallel while target localization is performed serially. The targets were oblique lines embedded in vertical lines and they popped-out from the display (parallel processing). Adding distractor items did not influence response latencies in the discrimination task. However, when participants were asked to localize the same targets (indicate whether one of the targets was located in one of the inside corners of the display), a pattern of results consistent with serial processing was obtained. The search process can be dependent upon the task participants have to perform. In this study, the discrimination task yielded radically different results than the localization task. Saarinen (1996b) also demonstrated that stimulus localization may not necessarily occur prior to stimulus identification. The difficulty of the localization task was manipulated while keeping constant the difficulty of the identification task: when the localization task was easy (large distance between the potential target locations), response times were faster for localization ("where") than for identification ("what"). However, when the localization task was difficult (by reducing the distance between the potential target locations), response times were faster for identification than for localization. Depending upon the difficulty of the task, radically opposite conclusions can be drawn: in one case one would conclude that localization occurs prior to identification. Yet in the other case, one would conclude that identification precedes localization.

Cognitive factors can also influence task difficulty. Kotary and Hoyer (1995) manipulated task difficulty by presenting target letters ("Q") without any distractor items, or by embedding the targets in a set of categorically (easy task) or conceptually (more difficult task) related distractor items. Two to five targets were presented in the condition where no distractor items were included. When the targets had a categorical relationship with the distractor items, the distractor items consisted of one letter which was varied across trials. The target letters "Q" could, for example, be embedded in an array of distractor items composed of the letter "B". When the targets had a conceptual relationship with the distractor items, the distractor items consisted of digits. The distractor digits could be consistent with the number of targets present in the display or be inconsistent with the number of targets. For example, when three targets were presented, the distractor items could be the digit "3" (consistent), or the digit "2" (inconsistent). The goal of their study was to look at the effect of age on the ability to inhibit distractor information in visual selective attention. Their results indicated that different levels of difficulty can give rise to different search functions. Both younger and older adults were impaired more when the distractors were conceptually interfering with the targets than when the interference was at the categorical level. In this study therefore, task difficulty had a similar impact on visual search for both younger and older participants. Counting the number of targets present in the display took increasingly more time as the task difficulty

increased (from targets only, to categorical relationship between targets and distractors, and finally to a conceptual relationship).

Folk and Lincourt (1996) also showed that the search slopes can be influenced by task difficulty. They used the visual search paradigm to study the effects of age on guided conjunction search. The amount of motion coherence within the distractor items was varied, making the task either easy (high coherence level) or difficult (low coherence level). They found that both age groups had reduced slopes (suggesting parallel processing) when the task was easy (when the distractor items oscillated coherently). It therefore appears that easier tasks were processed in parallel while more difficult tasks were processed serially.

Finally, task difficulty can be manipulated by varying the discriminability between the target and distractor items. Target-distractor discriminability can be manipulated in various ways. Practice can influence the level of discriminability, by making the target of search more familiar. Sireteanu and Rettenbach (1995), for example, found that under some circumstances, searches consistent with serial processing can become parallel with practice. In their experiments, participants performed a feature perception task. Participants underwent many testing sessions over a two day period. Two participants were extensively tested over a period of many months. Results show that a search which was initially consistent with serial processing became consistent with parallel processing over time. The

interpretation was that learning occurs as one performs a visual search task. This learning is not thought to be specific, but rather general and diffuse (likely due to an improvement in the overall search strategy). This can be thought of as an automatization process, where high levels of practice result in reflexive responses.

The familiarity of the stimuli used in the experimental setting can influence target-distractor discriminability, thus having an impact on task difficulty. von Grünau, Dubé, and Galera (1994b) conducted a series of visual search experiments using both familiar (digits and letters) and unfamiliar stimuli. Overall, they found that for both familiar and unfamiliar stimuli, manipulating the stimulus parameters to increase the discriminability between the target and the distractor items resulted in increased detection latencies. By manipulating the target-distractor discriminability in a different way (horizontal or vertical reflections or rotations), they found a larger impact of discriminability on familiar than on unfamiliar stimuli. They interpreted their results to support a continuum of perceived discriminability, and argued against a dichotomy between parallel and serial processing.

Nothdurft (1993) manipulated the saliency of the target in relation to the distractor items in a feature integration task. The target could be non-salient, salient within dimension, or salient across dimensions. In the salient within dimension condition, the target (a vertical line) was salient in orientation (the dimension which defined the target). In the salient-across-dimension condition,

the same target (a vertical line) was salient because of a local contrast in a different dimension (it had a different luminance contrast. The target did not pop-out due to its orientation (feature which defined the target), but rather due to its luminance. He found that when the target was non-salient (difficult task), search slopes consistent with serial processing were obtained. However, when the target was salient (easy task), search slopes consistent with parallel processing were found, regardless of whether the saliency was achieved within or across dimensions. Nothdurft interpreted his results to support the dichotomy between preattentive and attentive processing. He states that targets may be detected in two steps: 1) the saliency of the target allows for its localization and attracts attention to the proper area, and 2) more detailed processing occurs once attention is focused onto the target.

This dichotomous view can account for the results of Nothdurft (1993). A more parsimonious explanation, however, would be to view attention as a continuous process. One can think that there is a gradient along the saliency dimension, where increasing saliency gradually reduces task difficulty thus requiring less and less attentional resources. Zackon et al. (1997) demonstrated that various levels of attention can interact, suggesting that attention is not an all-or-nothing dichotomous process. They demonstrated an interaction between lower (subcortical) and higher (cortical) levels of attention by testing under both monocular and binocular conditions using the motion induction paradigm

(Hikosaka, Miyauchi, & Shimojo, 1993). A bar was presented between two cues such that the ends of the bar touched the cues. When the two cues were presented simultaneously, the perception was such that a collision was perceived in the centre of the bar (split priming effect). When an asynchrony was introduced between the presentation of the two cues, the collision appeared to be shifted away from the second cue (Faubert & von Grünau, 1995). It is assumed that the presentation of a cue creates an attentional gradient which degrades with time (von Grünau & Faubert, 1994a). Therefore, due to the passage of time, the gradient created around the first cue is weaker than the one created around the second cue, resulting in the described collision shift away from the second inducer. Participants had to indicate the location of the perceived collision point within the bar, and were tested both monocularly and binocularly while their eye movements were monitored. Monocular testing is useful in isolating midbrain attentional effects because of an anatomical asymmetry between the nasal and temporal fibers reaching the midbrain from the retina. The temporal hemifield is overrepresented in the midbrain in comparison to the nasal hemifield. The results showed that when the initial cue was presented to the temporal hemifield of the left eye, the strength of the motion induction effect was reduced in comparison to when the initial cue was presented to the nasal hemifield (the perceived collision was still away from the second cue, but was shifted away from the second cue). This indicates that the attentional gradient created around the cue presented in the

temporal hemifield of the left eye was greater than the one created around the nasal cue. This temporal hemifield presentation effect was not found for monocular right eye presentations. This can be explained by the fact that stimuli presented to the temporal hemifield of the left eye were the only ones capable of activating both the midbrain and the attentionally dominant right cortical hemisphere. Therefore, stimuli presented in the temporal hemifield of the left eye benefit from a subcortical attentional contribution in addition to the cortical contribution.

It appears that visual processing requires the contribution of the attentional system for all tasks, but to a different extent depending on whether the task is easy or difficult. This view contradicts that of Treisman and Gelade (1980) who proposed the feature integration theory. In this theory, feature perception is believed to occur at a preattentive stage, and to be indicative of parallel processing as shown by flat search functions. Feature integration requires attention, and is indicative of serial processing as shown by positively sloped search functions. The finding by many researchers that searches consistent with parallel processing can be obtained for feature integration tasks and that searches consistent with serial processing can be obtained for feature perception is inconsistent with the feature integration theory (which suggests that feature integration requires attention).

Treisman and Sato (1990) attempted to account for these findings by proposing a modified version of the original feature integration model. This revised model suggests that distractor items are inhibited by each feature map. Therefore, when searching for a red circle among red squares and green circles (conjunction search), the display would receive inhibition from the color map for all of the green objects, and would also receive inhibition from the shape map for all of the square objects. Under these conditions, only the red circle would not be inhibited and this target item would appear to pop-out from the display. This accounts for the fact that feature integration can be performed in parallel within the feature integration theory. However, Treisman and Sato did not address the impact that feature integration tasks conducted in parallel have on the basic postulate of the feature integration theory: that attentive processes are believed to be involved only in searches consistent with serial processing, which are obtained solely for feature integration tasks. These new findings indicate that under some conditions feature integration tasks can occur in parallel and therefore preattentively.

Posner et al. (1980) also proposed a dichotomous view of attention (the spotlight model). More recent work however, indicates a shift towards a continuous view of attention (Posner & Dehaene, 1994). They propose an attentional network at the physiological level, governed by the amplification and suppression of certain brain areas depending on the focus of attention and on the

stimuli and task. In this model, no clear cut-off point between preattentive and attentive processes is suggested. Rather, attention is viewed as a process distributed along a continuum, where different attentional levels may play a role depending upon the difficulty of the task.

I hypothesize that when confronted with an easy visual task (such as a red circle), it is likely that the visual system can process this information without requiring much attentional resources. However some attentional resources will be needed in as much as the subject needs to be at least minimally aroused to perform the task. Devoting more attentional resources to the display will probably not improve perception in a substantial way as the visual system is capable of processing the information. When the visual task becomes more difficult, however, visual perception will benefit from an increased allocation of attentional resources. Finally, when the visual task is extremely difficult, attention will be required to appropriately process the visual scene and to perform the task at hand. Since attention is not the property of a single brain area (attentional network), it is possible that different areas make different attentional contributions to visual processing.

In summary, I am proposing that attention is a process distributed along a continuum rather than an all-or-nothing dichotomous process. More specifically, I am hypothesizing that within the visual search paradigm, searches consistent with either parallel or serial processing can be obtained depending upon the difficulty

of the task, and regardless of whether feature perception or integration is involved. In the experiments described here, the discriminability between the target and the distractor items will be manipulated such that the task will be made easy in some conditions (high target-distractor discriminability) and difficult in other conditions (low target-distractor discriminability). Therefore, decreasing target-distractor discriminability can transform a feature perception task consistent with parallel processing into one yielding results consistent with serial processing (similar to those typically obtained for feature integration tasks). In the same way, increasing target-distractor discriminability (thus decreasing task difficulty) can transform a task associated with serial processing (feature integration task) into one which can be accomplished in parallel (typically found for feature perception tasks).

Three experiments were performed. The preliminary experiment was conducted to determine the target-distractor discriminability for each condition of Experiments 1 and 2. In Experiment 1, a feature perception task was used, while a feature integration task was used in Experiment 2. Two difficulty levels were tested in each experiment: easy and difficult.

PRELIMINARY STUDY

The goal of the preliminary study was to select the stimuli to be used in the two main experiments. Task difficulty in these experiments was defined as

target-distractor discriminability. Therefore, one needs to select two discriminability levels along this dimension of perception (i.e. orientation): one where the discriminability between the target and the distractor items is high and one where it is low. Both the easy and difficult stimuli must be discriminable; however, one should be highly discriminable (making the task easy) while the other should have low discriminability (making the task difficult). It was therefore assumed that the stimuli used for the two different difficulty levels were different enough from each other to tap into different processes. It was also assumed that in Experiments 1 and 2, the easy task required less attentional resources, while the difficult task required more attentional resources. The preliminary study consisted of a discrimination task performed at brief exposure durations. Increased error rates were interpreted as to imply a higher level task difficulty (reduced target-distractor discriminability).

Participants: Eight participants were tested in this experiment (five females and three males). Participants were aged between 16 and 42, with a mean age of 27.5. All participants were right-handed and had normal vision with no sign of strabismus or amblyopia.

Materials: Stimuli were presented on a RGB monitor controlled by a Macintosh Quadra 950 computer. All experiments were generated using the Psyscope program (Cohen, MacWhinney, Flatt, & Provost, 1993). The same materials were used in the two main experiments.

Stimuli and Procedure: The basic stimulus presentation is illustrated in Figure 1. The selected stimulus was a ring of the Landolt type (the ring was $2.10^\circ \times 2.39^\circ$ of visual angle with a $.95^\circ$ gap). All experiments in this study were conducted in a dimly lit room, and participants viewed the display from a distance of 60 centimeters while their chin leaned against a chinrest. Each trial started with the presentation of a fixation point. Participants were instructed to fixate and to initiate each trial by depressing the space bar on the computer keyboard. When the trial was initiated, two rings appeared on the screen, one to each side of fixation. On half the trials (100 trials), two distractor rings were presented (gap oriented at 0°). On the other half of the trials (100 trials), one of five different pairs of rings were presented (0° ring with either 10° , 20° , 45° , 70° or 90° leftward tilted rings) (twenty trials per pair). The leftward tilted ring, when present, was presented either to the left or right of fixation, at random. Participants were required to indicate whether the two rings had the same or different orientations, by depressing the left or right arrow keys, respectively. Following the presentation of the rings, a checkerboard mask pattern was presented, and remained visible on the screen until participants responded. Response latencies were not measured as response accuracy served as the dependent variable. Participants received no feedback regarding their performance level.

Figure 1. Stimulus configuration used in the preliminary experiment.

The experiment was performed in three separate blocks where the exposure duration was manipulated. The pairs of rings were presented for 15, 30 or 45 milliseconds. The order of exposure durations was randomized across participants. Overall, a total of 200 trials were conducted for each level of exposure duration. Each subject underwent 600 trials (200 trials X 3 exposure durations). Approximately 45 minutes were required to complete the three sessions of this experiment. Practice was given at the beginning of the first session, to familiarize participants with the task (approximately twenty practice trials were required for participants to feel confident about the task they were asked to perform).

Results: The results of the preliminary study are shown in Figure 2. The percent error rate is plotted as a function of the difference in orientation. An overall analysis of variance (ANOVA) showed that exposure duration had a significant effect on response accuracy ($F(2, 100) = 5.45, p < .05$). The orientation difference of the gaps of the two rings also produced a significant effect ($F(4, 100) = 78.91, p < .05$). No significant interaction was found between exposure duration and gap orientation.

The purpose of this study was to select two ring orientations, one which would be easily discriminable, and one which would be difficult to discriminate. Therefore, although the interaction was not significant, the results for the three exposure durations for each individual orientation were looked at separately.

Figure 2. Mean percent error rate (and standard error) as a function the difference in gap orientation between the two rings, for the three exposure durations used in the preliminary experiment.

When the difference in orientation between the two rings was small (10°), participants made a high percentage of errors regardless of exposure duration (the error rate is well above 50%). When the difference in orientation was large (90°), participants made very few errors in the discrimination task. For the intermediate orientation differences, the error rate is dependent upon orientation difference and exposure duration.

Discussion: The present experiment was conducted to assess which difference in ring orientation is necessary to discriminate between a target ring and a distractor ring with ease in one condition, and with difficulty in the other condition. The results show that when there is a 10° difference in orientation between the two rings, the error rate is high, regardless of exposure duration. This difference in orientation may be too difficult to detect; even when participants viewed the display at the longest exposure duration used in this experiment they could not accurately discriminate between the two rings. When the difference in orientation between the two rings was 20° , the target ring becomes discriminable from the distractor ring with an accuracy level greater than 80%, at exposure duration of 45 ms. Therefore, it seems that although it is difficult to discriminate between the two rings having this orientation difference (high percentage of errors at the shortest exposure duration), it is possible to do so when the exposure duration is long enough. This orientation difference was selected for the difficult tasks of Experiments 1 and 2. The performance for the 45° , 70° , and 90°

orientation differences yielded similar discrimination performance. The rings at all three orientation differences were discriminated with ease and high accuracy at all exposure durations. Any of the three orientations could have been selected for the easy condition. The 90° orientation difference was chosen. Therefore, in Experiments 1 and 2, the target for the easy condition will be a ring with its gap located at 90° to the left (a backward "C"), and the target in the difficult condition will be a ring with its gap located at 20° to the left of the vertical meridian.

The goal of Experiments 1 and 2 was to demonstrate that searches consistent with serial processing can be obtained for feature perception tasks and that searches consistent with parallel processing can be obtained for feature integration tasks. The type of search is hypothesized to depend on the difficulty of the task rather than on whether feature perception or integration is involved. In sum, it is impossible to conclude, based solely on the type of target involved in a search (feature perception or feature integration), whether attention contributes to the processing of the visual information. Rather, it seems more accurate to assume that attention is involved in all tasks, but to a different extent.

EXPERIMENT 1: FEATURE PERCEPTION

The goal of Experiment 1 was to demonstrate that a feature perception task can give rise to searches consistent with either parallel or serial processing, depending on the difficulty of the task.

Participants: Eight participants were tested in this experiment (6 females and 2 males). All participants but one were right-handed and the mean age was 27.9, ranging from 16 to 42. Participants from the preliminary study all participated in this experiment, with the exception of one.

Materials: The materials used in this experiment were identical to those in the preliminary experiment.

Stimuli and Procedure: This experiment consisted of two conditions, which were conducted in separate blocks. In the first condition, a visual search task was used, in which the target was the ring which was easily discriminated from the distractor item in the preliminary experiment (the gap was located 90° to the left of the vertical meridian). The distractor items consisted of rings with a gap located at the top; based on the results of the preliminary experiment, the target was highly discriminable from the distractor items. All rings (target and distractor items) were black, and were presented on a gray background of 8.61 candela per meter square.

Participants initiated each trial by depressing the space bar while fixating on a centrally located point. Participants were instructed to search for the target and to depress the left arrow key on the computer keyboard, using their dominant hand when the target was present (half the trials). When the target was absent, participants were required to depress the right arrow key on the keyboard. The display remained present on the screen until participants responded. Subject were

instructed to respond as rapidly as possible while maintaining a high level of accuracy. Within any given session, participants were required to be accurate on 80% of the trials. Performance below that criteria led to the rejection of that session, and participants would rerun the session. This accuracy criteria was selected based on the results of the preliminary experiment, which show that participants detected the 20° oriented ring with 80% accuracy at exposure duration of 45 ms. Detection latencies as well as response accuracy were collected. Auditory feedback was given to the participants to inform them of the accuracy of their responses on each trial. Two different tonalities were used, one for correct the other for incorrect responses.

This procedure followed for display sizes of 8, 16 and 24 distractor items which were run in blocked trials (the order in which each display size was run was counterbalanced across participants). For all display sizes, the items were arranged in 4 columns, with either 2, 4 or 6 rows (see Figure 3 for a detailed description of the display used in this condition: stimulus size and spacing was identical for all conditions of Experiments 1 and 2). For all display sizes, the target was presented equally often at eight randomly chosen locations. For display size of eight items, the target appeared at all locations; for display sizes of 16 and 24, eight locations were randomly chosen to serve as target location. These randomly chosen locations were different for each condition (easy and difficult). Three sessions were run for each display size. The first session was run for the

Figure 3. Easy stimulus configuration and measurements (degrees of visual angle) used in Experiment 1.

purposes of familiarizing participants with the task and the results were not included in the analysis. In each session, thirteen trials were run with the target present, and thirteen with the target absent, for a total of 26 trials per target location (eight overall). Therefore, in each session, 104 trials were conducted with the target present and 104 trials were conducted with the target absent. Overall, 208 trials were run in each session, and the results of two sessions were analyzed (416 trials).

The procedure for the second condition was identical to that of the first condition, with the exception that a different target was used. The target which was difficult to discriminate from the distractor item in the preliminary experiment was used (the gap is located 20° to the left of the vertical meridian). The stimulus configuration used in this condition is illustrated in Figure 4. Detection latencies were expected to increase as display size is increased. The first and second conditions were run separately, and the order of presentation was counterbalanced.

Results: *Reaction time:* A $3 \times 2 \times 2$ factorial analysis of variance (ANOVA) was conducted on the transformed reaction time data ($\log_{10}$). The data were transformed to ensure that the assumption of equal variance was not violated for the ANOVA. Even with this transformation, the assumption of normality which underlies the analysis of variance was violated; however, the ANOVA is quite robust to violations of the normality assumption when an equal

Figure 4. Difficult stimulus configuration used in Experiment 1.

number of participants are used in each experimental group. Eight participants were used in each experimental group in the present study, and the ANOVA can therefore be used with reasonable confidence (Keppel, 1991). The histograms, as well as graphs showing the relationship between the means and the variances are shown in Appendix A.

The three independent variables were display size (8, 16 and 24 items), target presence (present or absent) and task difficulty (easy or difficult). The dependent variable was the log 10 of the response latencies required to detect the target. The means for the overall transformed reaction time data for the trials on which a correct response was given are illustrated in Figure 5. The trials on which an incorrect response was given were excluded from the analysis. Significant main effects were found for display size ($F(2, 84) = 4.58, p < .05$), target presence ($F(1, 84) = 5.15, p < .05$) and task difficulty ($F(1, 84) = 60.09, p < .05$). The main effect of display size was followed-up with a multiple comparisons test (Tukey) to determine which groups significantly differed from each other. The results of this procedure show that only the 8 and 24 item groups significantly differ from each other ($p < .05$). A significant interaction was found between display size and task difficulty ($F(2, 84) = 7.19, p < .05$). A simple effect analysis showed that display size had a significant effect in the difficult condition ($F(2, 84) = 7.24, p < .05$), but not in the easy condition. No significant interactions were found between target presence and task difficulty, nor between display size and target presence. Finally,

Figure 5. Mean reaction time (and standard error) as a function of display size in Experiment 1 (feature perception).

the three-way interaction was not significant.

The best-fit linear regression line was found for each of the curves plotted in Figure 5. The slopes for the easy condition were -1.712 and -.776, for target present and absent respectively. The slopes for the difficult condition were 10.813 for target present and 30.192 for target absent. These slopes represent the average processing time required per item for the search.

Error rate: Participants were instructed to respond as rapidly as possible while keeping errors to a minimum. The error rates were therefore analyzed to ensure that although participants responded as fast as possible, they were accurate in their responses. The overall accuracy results are illustrated in Figure 6. The results show that the mean percent error rate for all conditions was well below the rejection criteria (20% error rate). Furthermore, the highest error rate obtained by any one subject was 18.8% (see Appendix B), which is within an acceptable range of errors. A three-way analysis of variance was run on the error data. The factors were task difficulty (easy and difficult), display size (8, 16, and 24 items), and target presence (present and absent). A main effect of task difficulty ($F(1, 84) = 14.84, p < .05$) and of target presence ($F(1, 84) = 49.73, p < .05$) were found. Display size did not produce a significant main effect. A significant interaction between task difficulty and target presence was also found ($F(1, 84) = 23.76, p < .05$). A simple effect analysis showed that target presence had a significant effect on error rates in the difficult condition ($F(1, 84) = 54.13, p < .05$), but not in the

Figure 6. Mean percent error rate (and standard error) as a function of display size for all conditions in Experiment 1.

easy condition. The interactions between task difficulty and display size, and between display size and target presence were not significant, nor was the three-way interaction.

Discussion: Overall, the error rate data indicate that participants were able to perform the task with an acceptable level of accuracy (well above 80% correct on average). Yet, participants did make mistakes, indicating that they were respecting the instructions and were responding as rapidly as possible. It therefore appears that the task was performed according to the instructions. The analysis ran on the error data shows that overall, error rate is different in the easy condition than in the difficult condition. Error rate is overall also significantly different in the present and absent conditions. The significant interaction between task difficulty and target presence indicates that target presence has a different effect depending on the level of task difficulty. In the easy condition, there is a significant effect of target presence, but not in the difficult condition.

The results from the reaction time data show that overall, increasing the number of distractor items present in the display increases detection latencies. More specifically, the effect of display size is found between the condition where 8 items are present and that where 24 items are present. Likewise, there is a difference in reaction time for those trials where the target was present in comparison to those where the target was absent. An interesting finding is that task difficulty influences response latencies. It seems that as the task was made

more difficult (by reducing the discriminability of the target among the distractor items) participants needed more time to detect the target. Mainly, however, there was a significant interaction between display size and task difficulty, showing that the effect of display size is different at each level of task difficulty. Display size has virtually no effect on reaction time when the task is easy, but influences reaction time when the task is difficult.

The slopes confirm that the search in the easy condition was conducted in parallel, as the slope for target present in this condition is well below 6 ms (-1.712). Treisman and Souther (1985) found that searches consistent with parallel processing are below 5-6 ms per item. The slope for target present in the difficult condition is indicative of serial processing as it is greater than 6 ms (10.813). Furthermore, a search consistent with serial processing is assumed to be self-terminating when the slope for target absent is approximately twice the slope obtained for target present. In the difficult condition the slope for target absent is approximately three times greater than the slope for target present. This suggests that participants did not end their search immediately following target detection (indicative of an exhaustive search strategy). A possible explanation is that as participants were required to keep errors to a minimum, they might have made sure that the target was not present in the target absent condition (making the search more similar to an exhaustive search of the display). Another possible explanation for the three-to-one ratio between target present and absent in the

difficult condition is that the error rate influenced the search functions. The error rate for target present in the difficult condition is higher than the error rate for target absent in the same condition. The higher error rate may indicate that participants responded faster in the target present condition (showing a speed-accuracy trade-off). The faster detection latencies may have contributed to a more shallow slope for target present in the difficult condition. This shallow slope increases the ratio between target present and target absent (three-to-one instead of the expected two-to-one).

In sum, the results of this experiment show that the manipulation of task difficulty (through changes in target-distractor discriminability) alters the search functions. When the task is easy (large orientation difference between target and distractor items), increasing the number of distractor items present in the display did not have an effect on detection latencies (consistent with parallel processing). However, when the task is difficult (small orientation difference between the target and distractor items), adding distractor items to the display leads to an increase in detection latencies (consistent with serial processing).

EXPERIMENT 2: FEATURE INTEGRATION

The goal of Experiment 2 is to show that both parallel and serial searches can be obtained for feature integration tasks, depending on the difficulty of the task. In this experiment, feature integration is defined according to the classic

model of Anne Treisman. The target differs from the distractor items by a combination of two features (i.e. color and orientation).

Participants: The same participants used in Experiment 1 were run in this experiment.

Materials: The materials used in this experiment were identical to those in the preliminary experiment and in Experiment 1.

Stimuli and Procedure: Two conditions were conducted as part of this experiment and they were run in separate blocks. The first condition was aimed at demonstrating that a search consistent with parallel processing can be obtained for a feature integration task if the task is easy (highly discriminable target). The target which was easily discriminated from the distractor item in the preliminary study was used in this condition (ring oriented 90° to the left of the vertical meridian), with the exception that it was yellow (28.70 cd/m^2). The distractor items consisted of yellow rings with 0° orientation, and of black rings with a leftward 90° orientation (see Figure 7). On those trials where the target was absent (half the trials), there was an equal number of black and yellow rings as well as an equal number of rings oriented at 0° and 90° . On those trials where the target was present, one of the 0° yellow rings from the target absent condition was replaced by a 90° yellow ring. The target was presented, in random order, equally often at one of eight possible locations (chosen randomly). Eight different

Figure 7. Easy stimulus configuration used in Experiment 2.

stimulus configurations were constructed (locations of the yellow and black distractor items within the display); therefore, eight different displays were used, one for each target location. Likewise, eight different stimulus configurations were constructed for the target absent condition. The target was present on half the trials, and participants were instructed to depress the left arrow as rapidly and accurately as possible when they detected the target. When the target was absent, participants were asked to depress the right arrow key on the computer keyboard. The display remained present on the screen until participants produced a response.

Three display sizes were tested and they consisted of either 8, 16 or 24 items. Thirteen trials were run for each possible target location when it was present, for a total of 104 trials. An equal number of trials were run when the target was absent. Overall, 208 trials were run in each session and participants took part in three sessions. The first session (practice) was excluded from the analysis and the results of the 416 trials of the following two sessions were analyzed. In this condition, display size was not expected to influence detection latencies as the task was easy (highly discriminable target); the target should pop-out from the display regardless of the number of distractor items present.

The second condition aimed at finding a search consistent with serial processing for a feature integration task. The target selected for this condition was the one which was difficult to discriminate from the distractor item in the preliminary study (ring oriented 20° to the left). The target was yellow in this

condition (as opposed to black in the preliminary study). The distractor items were yellow rings oriented at 0° and black rings with a 20° leftward orientation (see Figure 8). As in the first condition, on those trials where the target was absent, an equal number of black and yellow rings, as well as an equal number of upwards and leftwards oriented rings were presented. When the target was present, it replaced one of the yellow distractors found in the target absent condition. The target was presented, in random order, equally often at one of eight possible locations (chosen randomly). For each possible location, the configuration of the display (locations of the yellow and black distractor items) was varied; therefore, eight different displays were used, one for each target location. Likewise, eight different stimulus configurations were constructed for the target absent condition. The target was present on half the trials, and participants were instructed to depress the left arrow as rapidly and accurately as possible when they detected the target. When the target was absent, participants were asked to depress the right arrow key on the computer keyboard. The order of testing was counterbalanced such that half the participants received one condition first while the other half received the other condition first.

Three display sizes which consisted of either 8, 16 or 24 items were tested in separate blocks. Thirteen trials were run for each possible target location when it was present, for a total of 104 trials. An equal number of trials were run when the target was absent. Overall, 208 trials were run in each session and participants

Figure 8. Difficult stimulus configuration used in Experiment 2.

took part in three sessions. The first session was conducted to familiarize participants with the task and these results were not included in the analysis. Therefore, two sessions were included in the analysis (416 trials). In this condition, display size was expected to influence detection latencies as the task was difficult (not highly discriminable target); the target was not expected to pop-out from the display, and the target was expected to be searched for in a manner consistent with serial processing.

Results: *Reaction time:* A log 10 transformation was done on the data to ensure that the variance was equal across all experimental groups. A 3 X 2 X 2 factorial analysis of variance (ANOVA) was conducted on the transformed data. The assumption of normality was violated, but the results were used as the ANOVA is robust to such a violation when an equal number of participants are tested in each experimental group. In the present experiment, eight participants were tested in all conditions. Appendix A shows the histograms and the relationship between the means and the variances.

The three independent variables were display size (8, 16 and 24 items), target presence (present or absent) and task difficulty (easy or difficult). The dependent variable was the log 10 of the response latency to correctly detect the target. The overall results for the transformed data are illustrated in Figure 9 (incorrect trials were excluded from the analysis). A significant main effect of display size ($F(2, 84) = 10.77, p < .05$) was found. A multiple comparison

Figure 9. Mean reaction time (and standard error) as a function of display size in Experiment 2 (feature integration).

analysis (Tukey test) was performed to see which groups significantly differed from each other. The results of this analysis show that there is a significant difference between the 8 and 24 item conditions, and between the 16 and 24 item conditions ($p < .05$). However, no significant difference between the 8 and 16 item conditions was found. Significant main effects of target presence ($F(1, 84) = 5.18, p < .05$) and of task difficulty ($F(1, 84) = 35.31, p < .05$) were also found. The interaction between display size and task difficulty was significant ($F(2, 84) = 5.10, p < .05$). The effect of display size at each level of task difficulty was examined in a simple effect analysis: display size did not have a significant effect at the easy level of task difficulty. However when the task was difficult, display had a significant effect ($F(2, 84) = 13.20, p < .05$). No significant interactions were found between display size and target presence, and between target presence and task difficulty. The three-way interaction was not significant.

The best-fit linear regression line was drawn through the data of each condition. The slopes for the easy condition were 1.838 and 6.046 for target present and absent, respectively. The slope for target present in the difficult condition was 12.071, and the slope for target absent in the same condition was 27.111. The slopes represent the search time for each individual item.

Error rate: Participants were instructed to respond as rapidly as possible while keeping errors to a minimum. The error rate should therefore be looked at to ensure that although participants responded as rapidly as they could, they did

not sacrifice accuracy. The overall accuracy results are illustrated in Figure 10. The results show that the mean percent error rate for all conditions was low, but more importantly, that the highest error rate obtained by any individual subject (16.8%) was below the 20% rejection criteria (see Appendix B). A three-way analysis of variance (ANOVA) was performed on the error data. The factors were task difficulty (easy and difficult), display size (8, 16, and 24 items), and target presence (present and absent). The results from the analysis show that target presence produced a significant main effect ($F(1, 84) = 29.66, p < .05$). No other significant main effects were found. A significant interaction between task difficulty and target presence was found ($F(1, 84) = 4.74, p < .05$). A simple effect test was performed to examine the effect of target presence on error rate at each level of task difficulty. In both the easy ($F(1, 84) = 8.132, p < .05$), and difficult conditions ($F(1, 84) = 20.124, p < .05$), the effect of target presence was significant. The interactions between task difficulty and display size, and between display size and target presence were not significant. The three-way interaction was also non-significant.

Discussion: In both conditions of this experiment, participants performed the task according to the instructions: they responded as rapidly as possible while maintaining errors to a minimum, as indicated by the error rate data. Indeed, participants never made more than 20% errors, showing that they were responding with a high level of accuracy. However, the error rate was not equal to zero,

Figure 10. Mean percent error rate (and standard error) as a function of display size for all conditions in Experiment 2.

indicating that participants were responding as quickly as possible. The analysis performed on the error rate data shows that overall, the percentage of errors made was different for those trials on which the target was present than on those on which the target was absent (after allowing for the effects of display size and task difficulty). Furthermore, it was demonstrated that target presence had a significant effect on error rate in the two task difficulty conditions.

The results from the reaction time data show that overall, increasing the number of distractor items present in the display has a significant effect on detection latencies. Furthermore, there is a significant difference in detection latency depending on whether the target is present or absent, and on whether the task is easy or difficult. An interaction between display size and task difficulty indicates that the effect of display size is different at each level of task difficulty. Display size was expected to have no effect in the easy condition, but to significantly influence detection latencies in the difficult condition. This prediction was supported by the results.

The slopes confirm that the search in the easy condition was conducted in parallel, as the slope for target present in this condition is well below 6 ms per item (1.838 ms). The slope for target present in the difficult condition is indicative of serial processing as it is greater than 6 ms per item (12.071 ms). The slope for target absent in the difficult condition is 27.111, which is approximately twice the slope for target present. This is consistent with a serial self-terminating search. In

this experiment, the error rate for all conditions were comparable (i.e. the error rate was not dramatically different for one specific condition), perhaps accounting for the two-to-one ratio between target present and target absent in the difficult condition. No speed-accuracy trade-off occurred in any one specific condition. This suggests that the detection latencies were therefore not affected by the error data. The slopes of the search functions therefore reflect the underlying type of processing (self-terminating rather than exhaustive).

In sum, the results of this experiment show that the manipulation of task difficulty (through changes in target-distractor discriminability) alters the search functions. When the task is easy, increasing the number of distractor items present in the display does not have an effect on detection latencies (consistent with parallel processing). However, when the task is difficult, adding distractor items to the display leads to an increase in detection latencies (consistent with serial processing). The results, however, need to be interpreted with caution for the following reason: although the feature integration task used in this experiment was conform to the classic description proposed by Treisman and Gelade (1980), it could be argued that it was performed as a feature perception task rather than as a feature integration task. Indeed, because none of the black distractor items had the same orientation as the target, it is possible that participants altogether ignored the black distractor items and conducted their search within the yellow items only. If this was the case, then a feature perception task was performed, as the target

item differed from the yellow distractor items by only one feature (orientation). This is essentially what was proposed by Wolfe, Cave and Franzel (1989) in their guided search model. They suggest that visual search is guided towards the items which have a chance of being target items. Other items are ignored, thus transforming feature integration tasks in feature perception tasks. Additional experiments will be required to determine whether the stimulus configuration used in this experiment consisted of a true feature integration task.

GENERAL DISCUSSION

The present study was aimed at showing that attention is a process distributed along a continuum rather than a dichotomous process. Two experiments were conducted to test whether task difficulty could influence search functions in a visual search paradigm. A feature perception task was used in Experiment 1, while a feature integration task was used in Experiment 2. It was hypothesized that searches consistent with both parallel and serial processing could be obtained for either task, if the difficulty of the task was manipulated (by varying the target-distractor discriminability).

In Experiment 1 (feature perception task), it was hypothesized that by making the target less discriminable from the distractor items a search function consistent with serial processing could be obtained. Indeed, results consistent with both parallel and a serial processing were obtained in Experiment 1, depending

upon which stimulus configuration was used. When the task was easy, a search consistent with parallel processing was obtained, however when the task was difficult, a search consistent with serial processing emerged (adding distractor items resulted in slower detection latencies).

In Experiment 2 (feature integration task) the hypothesis was that evidence for either parallel or serial processing could be obtained depending on the level of discriminability of the target. Therefore, although the task involved feature integration, I proposed that when the target-distractor discriminability was high (making the task easier), search results consistent with parallel processing could be obtained. Search functions consistent with serial processing were obtained when the target-distractor discriminability was low (difficult task). More interestingly however, is that results suggesting parallel processing were obtained when the task was easy (high target-distractor discriminability).

In both experiments, the search functions obtained for the easy condition are consistent with parallel processing (search slopes < 6 ms per item). The search functions obtained for the difficult condition in both experiments are consistent with serial processing (search slopes $>$ than 6 ms per item). Search functions can have any level of steepness. At the two extreme poles, a search function can either be flat (consistent with parallel processing) or very steep (consistent with serial processing). There is a continuous range of steepness between these two poles. There is also a continuous range of task difficulty, and as one moves up the

difficulty continuum from easy to difficult, the search functions change from flat to steep.

The results from Experiments 1 and 2 are inconsistent with the feature integration theory proposed by Treisman and Gelade (1980). In their view, when the target differs from the distractor items by a single feature (feature perception task), the target is expected to pop-out from the display and to be readily available for detection, regardless of the number of distractors present in the display. In the present experiment, this occurred for high target-distractor discriminability, but not for low target-distractor discriminability. This therefore suggests that feature perception tasks can be processed in a serial manner when target-distractor discriminability is low (difficult tasks).

The feature integration theory also predicts that when a target is defined by a conjunction of two or more features (feature integration task), the search function should be consistent with serial processing. As Experiment 2 showed, this prediction is not always accurate. Increasing the target-distractor discriminability (easy tasks) produced a search function consistent with parallel processing. Again, the nature of the search is dependent upon task difficulty, not on the type of features.

The results obtained in the present experiments show that regardless of which task is used (either feature perception or integration), both parallel and serial searches can be obtained when target-distractor discriminability is

manipulated. Treisman and Sato (1990) revised the feature integration theory to account for the fact that parallel searches can sometimes be obtained for feature integration tasks. They propose that each feature is organized according to a specific map in which all locations are present. When a feature integration task is performed, all distractor items are inhibited by each feature map. Therefore, if one is searching for a blue triangle among red triangles and blue squares, all red items would receive inhibition from the color map, and all squares would receive inhibition from the shape map. The blue triangle would then be the only item in the display receiving no inhibition, and it would thus pop-out. This accounts for the parallel searches obtained for feature integration tasks. This revision to the feature integration theory, however, impacts on the basic concept on which it is based: that is that attention is required to integrate features into single elements. The revised model holds that feature integration tasks can be processed in parallel (without attention); this is in essence incompatible with the feature integration theory.

The results obtained in this study add to a growing body of evidence indicating that search functions in visual search tasks are not solely dependent upon feature type (perception or integration). Other factors can potentially influence visual search functions among which are: practice effects (Sireteanu & Rettenbach, 1995), overall number of items present in the display (Pashler, 1987), familiarity (von Grönau et al., 1994b), nature of the task (localization or

identification) (Saarinen, 1996a & b), response criteria (Hogeboom & van Leeuwen, 1997) and task complexity (Hogeboom & van Leeuwen, 1997; Folk & Lincourt, 1996; Kotary & Hoyer, 1995). This evidence suggests that attention may not be an all-or-nothing process, but that it rather may be distributed along a continuum.

Continuum vs. Dichotomy?

An ongoing debate in the literature pertains to whether attention is a process distributed along a continuum, or whether it is a dichotomous process (preattentive versus attentive). Treisman and Gelade (1980) hold that attention is a dichotomous process. Braun and Sagi (1991) also argue in favor of a dichotomy. Their argument is based on the fact that participants performed equally well in dual tasks as they did on a single task, when they had to detect a feature gradient as a secondary task. However, when the secondary task involved discriminating between letters, participants performed significantly worse in the dual task than they did in the single task condition. In short then, Braun and Sagi found that participants can perform letter discrimination as well as feature gradient detection in a single task situation. However, in a double task condition, letter discrimination was impaired but feature gradient detection was not when these tasks were performed as secondary tasks. This led them to believe that there has to be two distinct and separate processing systems (one preattentive and the other

attentive). The fact that engaging focal attention did not lead to diminished performance on a secondary task is indeed suggestive of dichotomous processing mechanisms. However, even Braun and Sagi did not completely reject the possibility that attention may be affecting the detection of feature gradient, although they conclude that such an influence appears to be at most marginal in their study. A study by Joseph, Chun and Nakayama (1997) suggests that in dual tasks similar to those used by Braun and Sagi attention may be required to process even those features which are usually assumed to be processed preattentively.

The dichotomous view of attention fails to account for results obtained in recent studies. In recent work, Posner and Dehaene (1994) suggested a continuous view of attention. They propose that attention has different effects at different processing stages within the visual system. In area V1, for example, attention is thought to have an inhibitory effect. These cells respond in a somewhat reflexive manner: the cells are highly activated when presented with their preferred stimulus. Therefore, attention could not have an excitatory effect at this processing level: attention can only have an inhibitory effect at this processing stage. It can modulate the firing rate of V1 cells such that some stimuli will receive less processing than others. As one moves up the processing stream, attention has an increasingly excitatory effect. That is because at higher processing level, cells respond in a less reflexive manner: attention can therefore boost the firing rate of such cells.

This view of attention is not dichotomous but rather suggests that attention may be distributed along a continuum. This suggestion is not that there is a processing mechanism which always operates without attentional involvement, and one which always operate with attention. Rather attention is viewed as a mechanism which can operate in various ways at all levels of processing, and which is "superimposed" in some sense over visual processing. Attention does not have to be involved for processing to occur, but it can influence visual processing at any stage of the visual system. The advantage of attention then is to facilitate the processing of important stimuli, either by inhibiting irrelevant stimuli or by enhancing relevant ones. Therefore in the Braun and Sagi (1991) study, the fact that feature gradient detection occurred while focal attention was engaged on a different task does not necessarily imply that there are two distinct and separate processing channels. One could account for their results in the following way: attention acted as to enhance the processing of the letter detection task, but did not inhibit lower level processing which allowed for the feature gradient detection task to occur without any apparent deficit. If, however, the focal attention task had been made more difficult in one way or another, then it is possible that the attentional system would have inhibited the lower level processes while enhancing the higher level processes. In this sense, the attentional system may be compared to a resource manager, ensuring that enough resources are devoted to adequately perform the most relevant task. In this sense then, viewing attention as

distributed along a continuum is not necessarily inconsistent with the fact that there may be processing channels which can operate without any attentional involvement. Depending on the nature of the stimuli, attention may or may not be involved in visual processing (although some minimal level of attentional arousal is expected to always be necessary).

Finally, the present view of attention is not inconsistent with others discussed earlier. For example, the distinction between exogenous and endogenous cueing can be retained within the attentional continuum. The type of cueing (exogenous or endogenous) is unrelated to how attention is distributed (continuum or dichotomy). Therefore, regardless of whether an exogenous or endogenous cue is used, attention will appropriately distribute the processing resources which are available to optimize visual processing. Furthermore, the fact that attention may distributed along a continuum is consistent with the idea that many brain areas are involved in attentional processing. Indeed attention is not believed to be the result of the activation of a single brain area nor is it believed to be the result of activation of the entire brain. Areas at various levels of processing (subcortical and cortical) are thought to be involved in attentional processing. If attentional processes are present throughout the brain, it is possible that different brain structures involved in attention have different ways of impacting on visual processing. Therefore, one could expect a broad range of attentional involvement depending on which structures are actually activated in various visual displays.

In conclusion then, I argue that attention is a process distributed along a continuum rather than a dichotomous all-or-nothing system. The fact that some studies show that some visual processing can be performed without the involvement of attention is not proof that a distinct and separate processing channel operates independently of attention. Nor is it proof that attention is always involved in visual processing. It is more likely that the allocation of attentional resources depends on the task at hand and on the available processing resources. The role attention will have on the structures responsible for visual processing is different depending on which structure is involved. An inhibitory effect is expected for lower level structures while an excitatory effect is expected for higher level structures.

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Distinguishing subcortical and cortical influences in visual attention.

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APPENDIX A

Histogram of raw data in Experiment 1

Histogram of transformed ($\log_{10}$) data in Experiment 1

Histogram for raw data in Experiment 2

Histogram for transformed dat (log 10) in Experiment 2

Relationship between means and variances in Experiment 1

Relationship between means and variances after a log 10 transformation in Experiment I

Relationship between means and variances in Experiment 2

Relationship between means and variances after a log 10 transformation in Experiment 2

APPENDIX B

Percent error rate for each subject in Experiment 1

Easy		Difficult										
Present			Absent			Present			Absent			
8	16	24	8	16	24	8	16	24	8	16	24	
AB	2.4	1.4	2.9	.5	.5	.5	4.3	5.8	6.3	.5	0	0
AD	7.2	11.1	10.6	4.8	4.3	3.4	9.1	18.8	13.5	1.4	1	1.9
AN	1.4	.5	1.4	.5	.5	.5	1.4	5.3	4.3	0	.5	1
BW	4.3	1.9	1.9	2.4	1.9	1.9	11.1	10.6	13.5	0	.5	.5
CT	1.9	1.9	2.4	1.9	0	2.4	1.9	4.3	5.3	.5	.5	.5
KS	1	1.4	1.4	1.4	1	1	6.3	12	16.3	3.4	1.4	3.4
LB	.5	2.9	2.4	1.9	2.4	.5	3.8	5.3	7.7	2.4	1.9	1
LR	1	1.4	2.9	1.4	1.9	1.4	4.3	6.7	7.2	1.4	.5	1

Percent error rate for each subject in Experiment 2

		Easy						Difficult					
		Present			Absent			Present			Absent		
		8	16	24	8	16	24	8	16	24	8	16	24
AB	2.9	5.8	6.3		1.4	1.9	.5	5.8	2.9	7.2	1	1	0
AD	3.8	7.7	11.1		3.4	3.4	4.8	9.6	8.7	11.5	1.4	1.9	0
AN	1	0	0		.5	0	0	1	1.4	1	1	0	0
BW	3.4	5.3	3.4		1.4	1	4.3	4.8	5.8	10.6	.5	1.9	.5
CT	.5	2.4	2.4		1.4	1	2.9	1.4	1.4	3.4	0	2.4	.5
KS	1.4	2.4	3.4		2.9	1.4	1	6.3	8.7	16.8	2.9	4.8	2.9
LB	2.9	4.8	5.3		1.4	2.4	2.9	1.4	3.4	6.3	1	1	1.4
LR	4.8	4.3	4.3		2.9	3.4	3.4	4.8	2.4	3.8	3.8	4.3	2.9

APPENDIX C

ANOVA summary table for the error data in the preliminary experiment.

Source	df	SS	MS	F	p
Exposure Duration	2	97.591	48.796	5.452	.006*
Orientation	4	2824.887	706.222	78.914	<.001*
Exp. Duration X Orientation	8	69.306	8.663	.968	.465
Residual	100	894.929	8.949		
Total	114	3871.391	33.960		

ANOVA summary table for the error rate data in Experiment 1.

Source	df	SS	MS	F	p
Task Difficulty	1	111.155	111.155	14.841	<.001*
Display Size	2	19.586	9.793	1.308	.276
Target Presence	1	372.488	372.488	49.734	<.001*
Task Difficulty X Display Size	2	14.286	7.143	.954	.389
Task Difficulty X Target Presence	1	177.943	177.943	23.759	<.001*
Display Size X Target Presence	2	31.241	15.620	2.086	.131
Task Diff. X Disp. Size X Target Pres.	2	11.863	5.932	.792	.456
Residual	84	629.126	7.490		
Total	95	1367.687	14.397		

Simple effect analysis: effect of target presence on the error rate at the easy level of task difficulty in Experiment 1.

Source	df	SS	MS	F	p
Target Presence	1	17.763	17.763	3.733	.060
Residual	46	218.876	4.758		
Total	47	236.639			

Simple effect analysis: effect of target presence on the error rate at the difficult level of task difficulty in Experiment 1.

Source	df	SS	MS	F	p
Target Presence	1	532.667	532.667	50.290	<.001*
Residual	46	487.226	10.592		
Total	47	1019.893			

ANOVA summary table for the transformed reaction time data in Experiment 1.

Source	df	SS	MS	F	p
Task Difficulty	1	.609	.609	60.092	<.001*
Display Size	2	.093	.046	4.481	.013*
Target Presence	1	.052	.052	5.146	.026*
Task Difficulty X Display Size	2	.146	.073	7.189	.001*
Task Difficulty X Target Presence	1	.033	.033	3.291	.073
Display Size X Target Presence	2	.018	.009	.888	.415
Task Diff. X Disp. Size X Target Pres.	2	.011	.006	.545	.582
Residual	84	.851	.010		
Total	95	1.812	.019		

Tukey test performed on the reaction time data in Experiment 1.

Comparison	Difference of Means	p	q	p < .05
8 vs. 24 items	.076	3	4.270	Yes*
16 vs. 24 items	.033	3	1.875	No
8 vs. 16 items	.043	3	2.395	No

Simple effect analysis: effect of display size on reaction time data at the easy level of task difficulty in Experiment 1.

Source	df	SS	MS	F	p
Display Size	2	.004	.002	.397	.675
Residual	84	.851	.010		
Total	95	1.812	.019		

Simple effect analysis: effect of display size on reaction time data at the difficult level of task difficulty in Experiment 1.

Source	df	SS	MS	F	p
Display Size	2	.234	.117	7.242	.002*
Residual	84	.851	.010		
Total	95	1.812	.019		

ANOVA summary table for the error rate data in Experiment 2.

Source	df	SS	MS	F	p
Task Difficulty	1	8.343	8.343	1.337	.251
Display Size	2	28.125	14.063	2.253	.111
Target Presence	1	185.093	185.093	29.660	<.001*
Task Difficulty X Display Size	2	1.075	.538	.086	.918
Task Difficulty X Target Presence	1	29.593	29.593	4.742	.032*
Display Size X Target Presence	2	28.533	14.266	2.286	.108
Task Diff. X Disp. Size X Target Pres.	2	21.165	10.583	1.696	.190
Residual	84	524.201	6.240		
Total	95	826.127	8.696		

Simple effect analysis: effect of target presence on error rate data at the easy level of task difficulty in Experiment 2.

Source	df	SS	MS	F	p
Target Presence	1	33.333	33.333	8.132	.006*
Residual	46	188.567	4.099		
Total	47	221.900			

Simple effect analysis: effect of target presence on error rate data at the difficult level of task difficulty in Experiment 2.

Source	df	SS	MS	F	p
Target Presence	1	181.352	181.352	20.124	<.001*
Residual	46	414.533	9.012		
Total	47	595.885			

ANOVA summary table for the transformed reaction time data in Experiment 2.

Source	df	SS	MS	F	p
Task Difficulty	1	.294	.294	35.312	<.001*
Display Size	2	.179	.090	10.766	<.001*
Target Presence	1	.043	.043	5.182	.025*
Task Difficulty X Display Size	2	.085	.043	5.104	.008*
Task Difficulty X Target Presence	1	.011	.011	1.323	.253
Display Size X Target Presence	2	.022	.011	1.324	.272
Task Diff. X Disp. Size X Target Pres.	2	.004	.002	.229	.796
Residual	84	.700	.008		
Total	95	1.339	.014		

Tukey test performed on the reaction time data in Experiment 2.

Comparison	Difference of Means	p	q	p < .05
8 vs. 24 items	.103	3	6.409	Yes*
16 vs. 24 items	.071	3	4.425	Yes*
8 vs. 16 items	.032	3	1.984	No

Simple effect analysis: effect of display size on reaction time data at the easy level of task difficulty in Experiment 2.

Source	df	SS	MS	F	p
Display Size	2	.011	.005	.682	.511
Residual	45	.347	.008		
Total	47	.358			

Simple effect analysis: effect of display size on reaction time data at the difficult level of task difficulty in Experiment 2.

Source	df	SS	MS	F	p
Display Size	2	.254	.127	13.199	<.001*
Residual	45	.433	.010		
Total	47	.687			

IMAGE EVALUATION TEST TARGET (QA-3)

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