

ATTENTIONAL SPATIAL SELECTION AND IDENTITY EXTRACTION ARE
SEPARABLE COGNITIVE PROCESSES

by

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ABSTRACT

While searching for objects in a cluttered environment, observers confront two tasks: selecting where to search, and identifying the targets. Chapter 1 reviews major theories of visual search, and highlights their approaches to these two functions. While anatomical, neurological, and behavioural evidence suggests dissociation between spatial selection and identity extraction, there is a vast controversy about this issue among visual-search accounts. This review demonstrates that none of these theories has adopted the right tool to independently manipulate the two functions. A new methodology is suggested in which the two functions are manipulated independently using spatial cueing to manipulate localization, and the attentional blink – AB - to manipulate identification (AB: impaired identification of the second of two briefly-displayed sequential targets).

In examining the separability of spatial selection and identity extraction, additive-factors logic is adopted: if two factors (here: spatial cueing and AB) influence independent stages of processing, they will have additive effects on the dependent measure. Conversely, whenever additivity occurs, the underlying mechanisms can be assumed to be independent.

Experiments in Chapter 2 show that cueing and the AB have additive effects, confirming the hypothesis that the two functions are separable. The results are accounted for by relating them to two major parallel pathways in the visual system: the dorsal and ventral pathways. Based on the characteristics of each pathway, it is plausible to assume that spatial cues (indexing spatial selection) are processed along the dorsal pathway while identification is processed along the ventral pathway. The two functions are therefore

separable because they are mediated by mechanisms that are anatomically and functionally distinct.

The experiment in Chapter 3 was designed to address contrary evidence regarding the separability of location and identity processing. It shows that those results were due to a procedural, artefactual ceiling. In Chapter 4, a prediction is tested based on the interpretation of results in the first study: if cueing involves both the dorsal and ventral pathways it should interfere with the AB; the results support this prediction. Chapter 5 discusses how these results collectively support the separability of spatial and identity processing, and also discusses future directions.

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To
those loved ones for whom this is a piece of memory of a piece of life...

and, to
Vince, who taught me much more than just how to do research...

PREFACE

The following is a manuscript-based rather than traditional dissertation. It begins with an introduction to the question addressed by this dissertation, both in terms of situating this question in the previous literature and in introducing the methodology used throughout the dissertation (Chapter 1). The following three self-contained chapters (Chapters 2-4) are manuscripts that are either submitted to or are in press in *Attention, Perception, & Psychophysics*, or are prepared for submission to similar journals. As a result of the choice to use a manuscript-based dissertation and to provide a general context for each manuscript, several sections of this document will appear similar and perhaps redundant. For instance, there is a great deal of similarity and overlap in the introduction to Chapter 1 and the introduction of various manuscripts presented throughout the dissertation, as well as between the method sections of the manuscripts presented in Chapters 2-4. Chapter 5 is a general discussion and contains several comparisons and analyses between the results presented in the previous chapters, as well as discussions and conclusions that relate the manuscripts together.

CO-AUTHORSHIP STATEMENT

The manuscripts presented in this dissertation were co-authored by my supervisor, Dr. James T. Enns and my co-supervisor, Dr. Vincent Di Lollo, who supervised me in each stage of the research process. The first manuscript (Chapter 2) was also co-authored by Dr. Raymond M. Klein, and the second and the third manuscripts (Chapters 3 and 4) were also co-authored by Dr. Thomas M. Spalek. Under my supervisors' guidance, I developed the theory that is examined in the dissertation, designed each of the studies, tested most of the participants, and performed all of the statistical analysis. I also prepared the first draft of the manuscripts and then worked closely with my supervisors to finalize them for publication. To recognize these collaborative efforts, plural pronouns (e.g., we, our, us) are used throughout the manuscripts.

CHAPTER 1

General Introduction¹

After more than a century of scientific study, attention is still one of the mysteries of cognitive science. This, of course, by no means implies that we know nothing about attention. In fact, several influential theories of attention have been developed based on psychophysical data, neuroimaging, single cell recordings, and clinical studies.

The term *attention* covers a very wide range of processes both in the behavioural and in the neurophysiological literature. In the present dissertation I use the term *attention* with reference to those cognitive mechanisms that enable us to select and further process a subset of the vast amount of information entering our sensory systems at any given moment in time.

The selection process might be voluntary (top-down, goal-directed) or involuntary (bottom-up, reflexive; e.g., see Corbetta & Shulman, 2002, for an up-to-date discussion of this distinction). When the selection process is voluntary, the system has a guiding principle or template as to what to look for. For example, imagine that when you set your computer browser to search for a specific word in a text, it highlights all the instances of that word. Now, all you need to do is to look for those highlighted words and see if any of those is the one you were looking for. On the other hand, if the selection process is reflexive, it is usually governed by the sudden onset of a stimulus. For example, if you are crossing a street while talking on your cell phone, a car horn's honk will attract your attention reflexively.

¹ Parts of this chapter will be submitted for publication. Ghorashi & Enns. Spatial selection and identity extraction: perspectives from theories of visual search.

A fundamental aspect of these selection processes is that they enable the system to allocate the limited resources available at any given time to more important stimuli, so that they can be processed further. This “further processing” usually involves consolidation and identification of the relevant stimulus to prepare the system for an appropriate response. From this perspective, attentional processing can be seen as having two distinct facets: spatial selection and identity extraction.

Either or both these processes have been studied with a variety of experimental paradigms such as single-cell recordings (e.g., Moran & Desimone, 1985; Snyder, Batista, & Andersen, 1997), brain imaging (e.g., Corbetta & Shulman, 2002), event-related potentials (ERP; e.g., Luck & Hillyard, 1994), and behavioural methods, notably visual search (e.g., Treisman & Gormican, 1988). Most of the studies in this dissertation involve visual search.

Visual search is among the most widely used and flexible tools for studying visual attention, especially in psychophysical studies. One reason for its popularity is that it clearly mimics tasks in the real world; in the wild, for example, predators are constantly searching for prey and prey for predators. Search is also a part of life for modern human beings as is evidenced when we try to design the most eye-catching advertisement or struggle to locate a specific word in a written document. Given these examples it is clear that search can be quite effortless if, for example, it involves a well-designed advertisement or if the word you are searching for is highlighted, but can be very difficult if the search circumstances are less than ideal, such as searching through a document which contains many words similar to the one you are searching for. Considering these issues leads us to the question of what, exactly, are the mechanisms of visual search?

Does the observer select a particular part of the visual field first to search for the target and then try to extract the identity of the items in that part of space, or does he or she identify the target first and then figures out its location? Even more fundamentally, are these two functions – spatial selection and identity extraction – two separable functions, or are they essentially the same function, occurring simultaneously and invariably in tandem? The answer to these questions could help us to further our understanding of visual search and whether or not it is a unitary phenomenon. This eventually will lead us to ask the same question about the unitarity of attention, which is still an ongoing debate.

To analyze the mechanism of visual search, researchers have distinguished between two types of search: the first is, easy or “pop-out” search in which the number of items in the display – or set size – does not affect the observer’s performance, and the second is difficult search in which performance is impaired as the set size increases. The behavioural measures most commonly employed by researchers are reaction time (or response time, RT) and accuracy. When RT is used, it is usually presented as a function of set size. This is called the *search slope*, which is flat when the target pops out, and is steep when the task is difficult (i.e., when performance is increasingly impaired as the set-size increases). Given this difference in slope between easy and difficult search tasks, it has been suggested that the search slope can serve as an index to distinguish between the two kinds of search (Treisman & Gelade, 1980), although this has been challenged by others (Johnston & Pashler, 1990; Palmer, 1994; Sagi & Julesz, 1985a). The presence of two distinct search functions has inspired researchers to suggest two different underlying mechanisms: parallel and serial search (Egeth, 1966; Neisser, 1967). Specifically, it has been suggested that in an easy search, the stimuli are analyzed in parallel, and therefore

the number of items in the search display does not matter. In a difficult search, however, the stimuli have to be processed sequentially, which makes the number of items an important factor.

As mentioned above, visual search has been used as a model task for understanding attention and its limits, and numerous theories of attention have been built around this task. Theories trying to account for the difference between easy and difficult search tasks have taken a variety of approaches. Some theories focus on the limitations of *spatial selection* of display items. Those models in which attention is likened to a spotlight (Eriksen & Hoffman, 1972; Posner, 1980), for example, emphasize the fact that a spotlight can shed light on a portion of the visual scene at any given time, and that, similarly, attention can be directed towards only one object or one area in space at any given time. By the same token, broadening the spotlight makes it less dense, reducing the processing rate (e.g., Barriopedro & Botella, 1998; Eriksen & St. James, 1986; Eriksen & Yeh, 1985).

Other theories, rather than focusing on spatial selection limits, focus instead on limitations in the process of *identity extraction*. For example, in theories in which the emphasis is on the similarity of items in the display (Duncan & Humphreys, 1989), it is the discriminability of the target that determines the difficulty of search. In the same way, those theories that emphasize the increasing probability of mistaking one of the distractors for the target as the set size increases (Eckstein, Thomas, Shimozaki, & Whiting, 1995; Palmer, Ames, & Lindsey, 1993) set the limitation of search performance in terms of identity extraction.

Aside from this controversy about the separability of the two functions of visual search, there are anatomical and neurological reasons to suspect that spatial selection and identity extraction may be separable functions. When two major pathways were recognized in the visual system (Ungerleider & Mishkin, 1982), they were described as underlying two separate functions. The dorsal and the ventral pathways were called “Where” and “What” pathways, respectively, because space-related processes such as motion and depth perception were shown to be carried out in the dorsal stream, whereas object identification was demonstrated to be the main engagement of the ventral stream. These two pathways involve two separate systems of neurons: magnocellular and parvocellular. Magnocellular neurons have relatively larger receptive fields and faster conduction rates than do parvocellular neurons. These attributes make them ideal for spatial selection tasks. In contrast, the ventral pathway consists mainly of parvocellular neurons, which have smaller receptive fields and slower conduction rates. These make the ventral pathway an ideal candidate for processing more identity-related characteristics such as colour and form. It does not seem implausible, therefore, to map the separability of spatial selection and identity extraction onto the dissociation of magnocellular and parvocellular systems – a dissociation that starts as early as in the retina. Moreover, patients have been reported who had either exclusive ventral stream damage, which leaves them with visual agnosia (Milner et al., 1991), or exclusive dorsal stream damage that makes them unable to reach for objects that they can verbally describe. The latter condition is called optic ataxia, which is often associated with Bálint’s syndrome (Bálint, 1909).

Similarly, behavioral studies with neurologically-intact subjects have also provided hints that spatial selection and identity extraction may be separable functions. It has been shown, for instance, that while the identification of an object interferes with the planning of reaching for another object (a ventral-pathway task), it does not interfere with the visually guided control necessary for completing the action (a dorsal-pathway task; Liu, Chua, & Enns, 2008). Also, there is evidence to support the occurrence of spatial selection without identity extraction for the target (Atkinson & Braddick, 1989; Ghorashi, Jefferies, Kawahara, & Watanabe, 2008).

The distinction between these two processes – spatial selection and identity extraction – is not explicitly delineated in some theories of visual search, while other theories have attempted to distinguish between them. In the next section, nine major theories of visual search are briefly reviewed with specific emphasis on whether and how this distinction has been made in each theory. The important point that is revealed by this review is how, even in those theories that distinguish between the two functions of search, the methodology used cannot, in principle, show the separability of the two functions of search. What is meant, here, by the separability of the two functions of search, is whether it is possible to see them function independently. Perhaps the most basic way to demonstrate this independence is to show that there are factors which can influence one of the functions without influencing the other. Therefore, after the following review shows how visual search studies did not use the suitable methodology to investigate separability of spatial selection and identity extraction, the basic rationale followed throughout the present dissertation will be discussed.

Theories of Visual Search

In this section, a brief review of nine theories of visual search is presented. The main objective is to see how each theory deals with the main question of the separability of the two functions of visual search: spatial selection and identity extraction. The nine theories reviewed here include the most eminent of those put forward during the last half century. Some of these theories, of course, have been more influential than others primarily to their ability to explain a greater number of empirical attention-related findings. The basis for their classification in this review, however, is solely how they deal with the question of the separability of the two functions of visual search.

Consequently, these theories have been assigned to one of the following categories: a) spatial selection and identity extraction are separable, and the temporal order in which they take place depends on the kind of search; b) spatial selection and identity extraction are distinct stages of search process, although spatial selection always occurs first; c) the separability of the two functions of search is not addressed explicitly in the theory; and d) spatial selection and identity extraction are not separable.

A) Separable functions; temporal order depends on the kind of search

One of the most influential theories of visual search belongs to this category: Feature Integration Theory. This theory postulates that, as will be discussed below in more detail, spatial selection always precedes identity extraction in conjunction search tasks, but in feature search it follows identity extraction.

Feature Integration Theory

Feature Integration Theory (FIT; Treisman, 1985; Treisman, 1988; Treisman, 1991; Treisman & Gelade, 1980; Treisman & Gormican, 1988; Treisman & Sato, 1990) is defined as an analyst or bottom-up approach to perceptual processing, rather than a synthetic or top-down approach. The latter family of theories proposes that objects are perceived holistically, and suggests that the holistic perception of the entire object precedes the perception of each feature. Feature Integration Theory proposes the exact opposite – specifically, that the basic features of objects such as colour, orientation, movement, spatial frequency, and brightness are processed first and are, in fact, the building blocks of perception. According to this view, feature analysis is the first step in the perception of an object, and it is carried out automatically and in parallel across the visual field. With each eye movement, all the basic features in the visual field are automatically sent to feature analyzers in the visual system. The spatial location of each feature is also coded in the *Master Map of Locations*, although this map is only referred to either when this spatial information must be accessed or when the target is defined by more than one feature (i.e., conjunction search). Namely, the first step in identifying a target is that its features are sent to the feature maps to be analyzed and identified. Although the spatial information about each feature is coded in the master map of locations, there is no need to refer to this map if the target is defined by one feature, because the critical feature of the target will be processed and identified in feature maps. If, on the other hand, the task is to report the location of that critical feature, then the additional process of localizing the feature target will be necessary, too. The same latter process is true if the target is defined by a conjunction of two features. That is, attention

will be needed to search through the master map of locations to combine the two critical features, and thus, the process of localization will occur inevitably before the identification of the conjunction target.

FIT proposes that attention serves as a kind of metaphorical “glue” that binds these various features represented in the master map of locations together into objects. Without that glue (i.e., if attention is deployed to another area of the visual field, or if for any reason no attentional resources accessible) the features cannot be combined into a coherent object. The now “free-floating” features are subject to illusory conjunctions, which occur when features are assigned to the wrong object because of the lack of attention.

FIT emphasizes the distinction between feature and conjunction search. The mechanism proposed to underlie feature search is the parallel processing of features, whereas the mechanism underlying conjunction search is the sequential processing of items for two features. In conjunction search, the target is defined by two features, and in order to find the target among distractors, the observer must search the items first for one feature and then again for the second feature. FIT uses flat and steep search slopes to index parallel and serial search tasks, respectively.

Another important characteristic of difficult search in FIT is that the search slope for target-absent trials is twice as steep as search slopes for target-present trials. According to FIT, this stems naturally from the self-terminating nature of the search. In difficult searches, on target-present trials, the observer finds the target after examining, on average, half of the items. On target-absent trials, however, the observer must examine all of the items in the display before deciding that the target is absent. This

results in a search slope that is twice as steep for target-absent trials than for target-present trials. In easy searches, on the other hand, the target-present/target-absent slope ratio will increase, even up to 8:1. The rationale is that in this type of search, when the target is present it pops out and renders a flat slope, whereas when the target is absent, the observer still tends to scan the entire scene searching for the target, although not in a completely serial manner.

In summary, Feature Integration Theory hypothesizes that because features are processed separately in distinct feature maps, these separable features a) lead to a parallel search; b) produce illusory conjunction in the absence of attention; c) can be identified without being located; and d) can have behavioural effects even when unattended, because their identification does not require attention. Conjunctions, on the other hand a) lead to a serial search; b) have no effect on performance unless focally attended (because they cannot be identified unless focally attended); and c) yield highly correlated performance in the tasks of identification and location, because referring to the master map of locations and hence, localization, is an inevitable step before their identification.

Spatial selection and identity extraction in FIT:

In FIT, the location of a conjunction target is gained before its identity, because attention must be focused on the master map of locations to combine the critical features and thus make them identifiable. Namely, if the observer has identified the target, it means that attention has already been focused on the target, since that is the only way for the target to be identified in conjunction search. Therefore, although spatial selection and identity extraction are distinct stages in conjunction search, spatial selection necessarily should precede identity extraction. This, however, is not the case for feature targets since

they can be processed at the level of individual features and therefore focused attention is not required. Given that focal attention is not required to process features, it is possible to perceive a feature target without localizing it. That is to say, the two functions of search are separate, and they operate independently in feature search. In conjunction search, in contrast, spatial selection necessarily precedes identity extraction, because attention needs to focus on a certain part of the master map of locations so that the features on the same location can be processed and glued together.

B) Distinct (though not necessarily independent) functions; spatial selection occurs

first

“Where” before “What”

According to this account (Atkinson & Braddick, 1989; Sagi & Julesz, 1985b) the process of detecting a target (whether it is present or absent) and localizing it precede the process of discriminating (identifying) the target. In order to test this, Sagi and Julesz used an orientation gradient of tilted line segments among which were a few horizontal or vertical lines. In some blocks of the experiment observers had to report how many oddball line segments – regardless of their orientation – were present (detection task). In other blocks, they had to report whether or not all the oddball line segments had the same orientation (discrimination task). They found that in the detection task the set size did not affect the observers’ performance, whereas in the discrimination task it did. In FIT’s terminology, this means that the detection task does not require attention, but the discrimination task does. This is despite the fact that in the discrimination task, the target differed from the distractors in only one feature: orientation. Thus, according to FIT, this task should have yielded a flat search slope.

In a subsequent experiment, they showed that observers were equally accurate in performing the detection and the localization tasks. They concluded that detecting and localizing a feature target in a search task (at least in an orientation task) do not require focal attention (and hence, a flat search slope). Nevertheless, identifying (discriminating) a target, although the target was not defined as a combination of features, did require focal attention (and hence, a steep search slope). This is because, they explained, the first – pre-attentive – step in the process of finding the target is to find a defect in the feature gradients, which allows for localizing the target but not for identifying it. Identification of the target requires focal attention.

Spatial selection and identity extraction in this account:

Following in the footsteps of Sagi and Julesz (1985a, 1985b), Atkinson and Braddick (1989) fine-tuned their experiment and demonstrated that it was easier for observers to make a decision about the coarse location of the target than to make a decision about either the fine location or the identity of the target. They proposed two possible explanations of their results:

- a) Both coarse and fine localization can be completely independent of identification process. Both localization processes are based on detecting a defect in the feature gradients, and the only difference between these two localization processes is that fine localization requires more time.
- b) Coarse localization is different from both fine localization and identification. Coarse localization can take place based on the detection of a gradient difference, but once focal attention is drawn towards that general

area of visual field, narrowing the focus of attention will lead to both a fine localization and identification of the target.

Atkinson and Braddick's (1989) experiment does not yield a conclusive answer to which explanation is more accurate. What is clear from both explanations, however, is that there is a necessary differentiation between localization (at least the initial, coarse localization), and identification. Moreover, they emphasize that the coarse localization process always precedes the localization process. Thus, in this account of visual search, spatial selection and identity extraction are considered to be distinct (but not necessarily separable) functions.

Guided Search

This account (Wolfe, 1994; Wolfe, 2006; Wolfe, Cave, & Franzel, 1989; Wolfe & Gancarz, 1996) developed from Feature Integration Theory (Treisman & Gelade, 1980) in the sense that in its early versions it also assumed a parallel and a serial stage for the search, one for features and one for conjunctions. The difference was, however, that in Guided Search all searches require focal attention; the difference between easy and difficult search lies instead in the "guidance" process. If the target differs from the distractors in a single feature, the guidance process is perfect, attention will be focused on the target immediately, and the number of distractors will not have an effect on performance. If, on the other hand, the distractors and the targets differ on more than one feature dimension, the guidance process is no longer perfect and the items must be examined in a serial manner, leading to a steep search function.

In this account, the attentional system is modeled as follows. First, all visual input is collected from the scene in a parallel manner. Most of the input goes through a

“selective processing” bottleneck, an important serial stage that is what is meant by “attention” in this account of visual search. The output from this stage results in object recognition. This selective process, however, is guided by information from the parallel stages of processing that took place at the initial stages of visual processing. There are some aspects of scene analysis that can bypass the selective bottleneck (and this information can influence the selective process), but then all of this information, as well as information from object recognition processes, has to go through yet another bottleneck called the attentional blink (AB; Raymond, Shapiro, & Arnell, 1992; Chun & Potter, 1995; Shapiro, 1994) bottleneck. This model, therefore, is a parallel-serial hybrid. Namely, visual information enters the system in parallel, selection of the items has to be carried out in series, but then processing of items (object recognition) can be performed in parallel again. The metaphor that is used in Guided Search for this selective process is a carwash, wherein cars have to enter sequentially, but then they can be washed (processed) in parallel inside the carwash.

The nature of guidance in this model is as a “control” signal, not an independent stage in the pathway. In the early versions of this model, the guidance stage served as the first stage of search, the input from which would be transferred to the selection process. In the most recent version, however, the guidance loop is a minor loop that receives input from the early stages of visual processing, and then if there is any signal that can provide guidance, it will be sent to the selective processing stage. The guidance can take place in two different ways: bottom-up or top-down.

Bottom-up guidance depends on how salient an item is. The salience of an item is calculated as the difference signal between the item and each of its neighbouring items.

That is, the greater the difference between the pairs of items, the greater the salience signal. Salience is also influenced by the physical distance between the items; the closer the neighbouring items are, the greater will be their effect on the salience signal.

In contrast to bottom-up guidance, top-down guidance involves applying more weight to the desired channels. If, for example, the target is a left-tilted line amongst vertical or right-tilted distractors, then the “left” channel will be assigned a larger weight. It must be noted that in the Guided Search model, the reentrant processes (Ahissar & Hochstein, 1997; Di Lollo, Enns, & Rensink, 2000) that would allow for this “weighting” or “template matching” to occur are not represented.

The overall signal created from the sum of the bottom-up and top-down signals is the final guidance signal, or the “activation map”. According to this model, the bottom-up signal weight can never be zero – the implication of this is that if there is a salient but irrelevant item, attentional capture is always a possibility.

Spatial selection and identity extraction in Guided Search:

In the Guided Search account, spatial selection is not explicitly discussed. As mentioned above, in the most recent version of Guided Search, all information – bottom-up and top-down – that is used in guiding the spotlight of attention is summed up in the “activation map”. This whole mechanism, however, is not necessarily always a part of the search process, because if search is a difficult one, the guiding signal would be very weak, leaving the identification alone in finding the target serially. If, on the other hand, the control signal is stronger, selection could take place to guide the identification process. This may imply that in Guided Search, the two functions of search are

considered to be distinct processes, even though how separable they are is not clearly discussed in this account.

Dimensional Weighting Account

The Dimensional Weighting account (Müller, Heller, & Ziegler, 1995) is in essence an extension of both Feature Integration Theory (Treisman & Gelade, 1980) and the Guided Search model (Cave & Wolfe, 1990). According to the Dimensional Weighting account, neither Feature Integration Theory nor the Guided Search model can explain the cost in the level of the y-intercept that occurs in a pop-out search task in which observers are searching for an “unknown” target that can be defined in more than one dimension (i.e., the target can be defined by one of two dimensions but which one is not known in advance).

Imagine a pop-out search task in which the distractors are small vertical grey bars. The within-dimension target is defined as a small gray bar which is either horizontal or is tilted slightly to the left or the right. A cross-dimensional target, in contrast, is defined as a small black vertical bar, a large vertical grey bar, or a small tilted grey bar. The Response Time x Set Size functions in both cases (within-dimension and cross-dimensional) are flat, but there is a y-intercept difference between the two conditions: advance knowledge of the dimension in which the target is defined leads to an improvement in overall performance. This difference, according to the Dimensional Weighting account, is explainable only if we assume there are dimension-specific maps in addition to the master map of locations.

Although these dimension-specific maps can be explained in Guided Search, in FIT it is assumed that saliency signals from different modules (or feature analyzers) go to a

saliency signal master map. There, the master map can determine whether there is an oddball in the display, and if there is, where its location is. It has no idea, however, about the dimension in which the oddball differs from the rest of the items in the display.

Based on this assumption, if a decision about the target in a feature search can be made considering only the master map of activations, and if all the observers need to do is to decide whether there is heterogeneity in the display, then the difference between the “known” and “unknown” conditions should disappear. In other words, if the task is simply to say if the display is heterogeneous or homogeneous, it should not matter whether the difference is only in one dimension (“known” condition) or in one of several dimensions (“unknown” condition). The results of the Müller, Heller, and Ziegler’s (1995) study show otherwise. Namely, in the unknown condition, when the potential feature target can occur in one of several features, the decision as to whether there is an oddball in the display cannot be made in the same way as when the target feature is known in advance. The knowledge of the source of the dimension from which the target comes from is necessary. This means that the top-down signals have an important effect on the bottom-up signals.

The proposed model assumes that “weighted” samples from the dimension-specific maps end up in the master map of activations. Greater weights will be assigned to the more important or more relevant features and less important features will be inhibited. In the master map, therefore, those signals with greater weight assigned to them can reach the necessary threshold much more readily than the features that are supposed to be ignored. If an irrelevant feature is highly salient, however, there is a possibility that its sample in the master map can also produce a strong signal that could pass the threshold,

and thus, affect the attentional processes. This explains the results of those studies (Theeuwes, 1991, 1992) that show that salient stimuli, even if irrelevant, have a distraction effect, without agreeing with the suggestion that top-down processes do not give priority to the relevant stimuli (Theeuwes, 1991).

Spatial selection and identity extraction in the Dimensional Weighting account:

This account is primarily concerned with how to find targets whose definitional features are unknown (i.e., there are several possible features that could define the target on any given trial). To this end, it builds on the structure of the FIT's master map of locations. The master map samples from dimension-specific maps, each of which provides saliency information for a different feature. The master map's sampling of the dimension-specific maps is weighted based on top-down control or on information from the previous trial. The important point is that location information is inherently built into the master map. Therefore, in the Dimensional Weighting account, as in the conjunction search in FIT, spatial information is gained with at least theoretical priority to identity information.

Johnston and Pashler's Account: Identity and Location Are Closely Bound

In this next account of visual search (Johnston & Pashler, 1990) it is suggested that in general, whenever localization is possible, identification is also possible, although the reverse is not always true. In trying to solve the controversy about localization and identification in visual search accounts, and to find out which function occurs prior to the other, Johnston and Pashler argue that they found three common problems in many studies of visual search:

A) The “different properties” problem. According to Johnston and Pashler (1990), in many studies investigating localization and identification, the investigators use one feature to measure localization and a different feature to measure identification. For instance, if the two targets are letters C or G among distractors which are filled black squares, and if the search array is displayed for a short amount of time, observers can use the amount of *luminance* to localize the target – regardless of its identity – but they need to use the small difference in *form* between C and G to discriminate between them.

B) The “negative information” problem. Imagine a situation in which the observer knows that the targets will be one of two types: orange or the letter H. If the observers notice that they can detect one of the target types – say orange – better than the other, then in those trials in which they cannot detect the target they can guess that it more likely was an H. In this case, they will be able to guess the identity of the target better than chance, but not its location.

C) The “location reporting” problem. Even if the observers can perceive the location of the target, they still need to translate it into the experimenter’s coordinates to be able to report it. However, if the experimenter’s coordinates do not match with the real target location, a reporting error could occur. For example, if the mask that is presented after the short display of the search array marks different locations on the screen than where the actual target locations were, then the observers can make a mistake in reporting the target location, even though they had correctly perceived it.

Johnston and Pashler (1990) attempted to avoid these limitations by making appropriate changes to the existing visual search methodology at the time. First, by adopting the same stimuli that Treisman and Gelade (1980) used in their experiment XIII

and IX, Johnston and Pashler tried to avoid the “different properties” problem. In those two experiments in Treisman and Gelade’s study, distractors were pink Os and blue Xs, and targets were either orange (O or X) or the letter H (pink or blue). Therefore, each target differed from the distractors only in one feature, and “it hardly seems likely that the color orange and horizontal line orientation (or any form feature in H) share a common property not in the background (distractors) that would specify the target without permitting its identification” (p. 845, Johnston & Pashler, 1990).

They also tried to equalize the difficulty of their targets and to let the observers choose a “no target” response to minimize the “negative information” problem. To avoid the “location reporting” problem, they provided anchoring points for the observers, and used the same geometrical arrangement for their mask, so that the observers could report the location of the targets more accurately. In two experiments, they observed that with feature targets, whenever the identity of the target was reported correctly, so was its location. On the other hand, only in 10% of the trials when the location was reported correctly the identity was not. Johnston and Pashler interpreted this as meaning that “perception of feature location and feature identity are closely but not quite perfectly bound together” (p. 852). The exact mechanism by which they explain their results is discussed below.

Spatial selection and identity extraction in Johnston and Pashler’s account:

According to Johnston and Pashler’s (1990) account of visual search, identification of a feature cannot occur before its localization, and therefore, FIT’s results must be explained in terms of either guessing artefacts or reporting artefacts. It is also different from Sagi and Julesz’s (1985a, b) account in how it explains the identity computation

process. In Sagi and Julesz's model, a heterogeneity in the gradient is first detected in the search array. This will produce an interrupt signal that calls for attention to be drawn towards that specific location in the array, which in turn will lead to identification of the target. In Johnston and Pashler's account, on the other hand, it is the pre-attentively computed feature identity that produces the interrupt signal. After the interrupt signal's service (call for attention), the identity information will be transferred to the central processor. In those infrequent trials in which this transfer is interrupted by the mask, the identity of the target will be missed, even though its location is reported correctly. This explains why the processes of localization and identification, although not identical, are so closely bound.

C) Separability of search functions is not explicitly addressed

In this section three theories of visual search will be reviewed. These three theories, although considered as distinct accounts of visual search, have many similarities, one of which is that they do not address spatial selection explicitly. For this reason, the role of spatial selection and identity extraction in all of these theories will be discussed together at the end of this section.

Two-Stage Model

In the Two-Stage model (Neisser, 1967; Hoffman, 1978; Hoffman, 1979) visual search is described as taking place in two sequential stages: an initial pre-attentive, parallel stage that guides the following serial stage. Stage 1 is where the items in the visual field are compared to the memory set and a score is assigned based on the degree of similarity. Thus, the two important factors in the first stage are the similarity between each item and the memory set, and the number of items in the search display. The

number of items is important because it decreases the signal-to-noise ratio for the target among the distractors. As a result, whenever the signal-to-noise ratio is low – either because there are too many items or because the similarity between items is too great – the error rate increases if the response is based only on the output of Stage 1. To increase the accuracy, a list of target candidates is transferred to Stage 2, where each item is subjected to closer scrutiny, one by one. The process of transfer per se is a serial process. Whichever item has the largest signal-to-noise ratio score will be the first candidate to be transferred. Hence, if the first selected (“attended to”) item has a large signal-to-noise ratio score, the search process will end after examining the first item. If, on the other hand, the current trial is a target-absent trial or if all the items have very small signal-to-noise ratio scores, the serial process of selection and transfer must continue until almost all of the items are examined in Stage 2 (Hoffman, 1979).

Stage 2, unlike stage 1, is a serial stage where items are compared with the memory set one by one. Depending on the transfer rate (i.e., the selection/attention process), items might need to be stored in iconic memory until Stage 2 is again free after processing the previous item. Misses, therefore, are either due to a low signal-to-noise ratio that prevents the target from making it to the candidate list, or due to the target representation degrading from being stored for too long in iconic memory prior to entering Stage 2. In general, in this model “the high speed of visual search is possible because the slow stages responsible for selective attention and memory comparison are guided by an initial parallel analysis of all display items” (Hoffman, 1979, p. 326).

Resemblance Account

In this account (Duncan & Humphreys, 1989), as it is obvious from the title, the most important factor responsible for the difficulty of a search task is similarity among the stimuli in the search array. In brief, greater similarity between targets and non-targets and less similarity between non-targets results in an increase in the difficulty of the search. Therefore, feature search and conjunction search are not fundamentally different from each other – they differ only in terms of the degree of similarity between the target and the distractors.

This account, like the Dimensional Weighting account (Müller, Heller, & Ziegler, 1995) assumes that input stimuli to the visual system gain weight based on their relevance to the task at hand. If the stimuli match the internal template for the current task, they gain more weight. Unlike the Dimensional Weighting account, however, in the Resemblance account, perceptual grouping helps non-targets to be inhibited – a process that can take place at a parallel stage to allow more important (more heavily weighted) stimuli to gain access to visual short-term memory (VSTM). This inhibition can spread to all similar stimuli, allowing a greater number of non-targets to be ruled out with little effort. In fact, in a connectionist model of visual search (SERR; Humphreys & Müller, 1993) based on the Resemblance account, initial search processes are proposed to be parallel because they operate through the perceptual grouping of distractor items. Given evidence that surface properties such as surface junctions (Enns & Rensink, 1991), 3-D attributes (Enns, 1990; Enns & Rensink, 1990), direction of lighting of the surface (Ramachandran, 1988), and shadow cues (Rensink & Cavanagh, 1993) can lead to a fast search, it has been suggested (Grossberg, Mingolla, & Ross, 1994) that grouping

processes make it possible to have much more complicated multi-item pre-attentive perceptual units rather than plain features.

In four experiments, Duncan and Humphreys (1989) show how: a) the size of the stimuli changes the effect of the display set size, b) search through heterogeneous non-targets is extraordinarily difficult, and c) highly similar targets and non-targets make the search difficult. Their four general principles are as follows:

- 1) Search efficiency varies continuously (there is no such a dichotomy as serial/parallel).
- 2) Increasing target/non-target similarity leads to a decrease in search efficiency.
- 3) Decreasing non-target/non-target similarity leads to a decrease in search efficiency.
- 4) Increasing target/non-target similarity has little effect when non-target/non-target similarity is high. In the same way, decreasing non-target/non-target similarity has little effect if target/non-target similarity is low.

In summary, the Resemblance account of visual search has three basic components:

1. In the first step, information from the whole visual field is collected in a parallel manner.
2. Then, this information is compared to the internal template for the task at hand and the most relevant information is selected.
3. Finally, the selected information is sent to visual short-term memory for further analysis and processing. Since VSTM has a very limited capacity, however, it needs to be emptied for the next use, which is done by re-

fixation. Thus, the search process consists of both parallel and serial components: each process of filling the VSTM is carried out in parallel, whereas moving from one of these periods to the next is performed in a serial manner.

Signal-Detection-Theory Based Model

Many aspects of search are said to be explained simply by a signal-detection-theory (SDT) based model (Cameron, Tai, Eckstein, & Carrasco, 2004; Eckstein, 1998; Eckstein, Thomas, Palmer, & Shimozaki, 2000; Eckstein, Thomas, Shimozaki, & Whiting, 1995; Geisler & Chou, 1995; Palmer, 1995; Palmer, Ames, & Lindsey, 1993; Palmer & McLean, 1995; Palmer, Verghese, & Pavel, 2000; Verghese, 2001). Since SDT was introduced in psychology (Peterson & Birdsall, 1953; Tanner & Swets, 1954), it has been used to explain the perception of near-threshold stimuli according to the number of hits, misses, false alarms, and correct rejections, and how the observers' biases changes their decision-making behaviour. Given that the task in a search is to find a target among the distractors, or to respond to the "signal" among some noise, it is logical to apply the same idea in a search process, too.

In this model, the feature(s) that define the target, or the way the discriminability of the target from the distractors is manipulated is irrelevant. What is important is to keep all these factors constant as the number of distractors increases. The basic principle is that each item in the display produces an internal response in the observer (Eckstein et al., 2000). In general, the internal response to the target is assumed to be larger than the response to the distractors in most of the trials, unless for some reason the internal noise

increases the response to the distractors. This larger internal response will be chosen as the final response for the current trial.

If the distributions of responses to the distractors and to the target are presented as two probability distributions, the difference between the means of the two distributions divided by the standard deviation of the distributions (assumed to be the same) is an indicator of the discriminability of the target from the distractors (d'). When discriminability between the target and the distractors is high, set size does not have that much of effect on the proportion of correct identification of the target. This is parallel search in FIT's terminology. As discriminability decreases, however, the effect of set size increases, although this increase is not linear.

Spatial selection and identity extraction in these three accounts:

In each of the Resemblance account and the SDT-based account, one aspect of the Two-Stage model is more deeply examined and emphasized. In the Two-Stage model of visual search, the strength of the output signal of stage 1 depends on how similar the target is to the distractors; the less the similarity, the greater the likelihood that the target will be the first item to be sent to stage 2 (or if salient enough, it might not need to be sent to stage 2 at all), and the sooner the search will end successfully. The similarity among the target and the distractors, as well as among the distractors themselves, and how these similarities affect the difficulty of search is the main subject of the Resemblance account.

Another main point in the Two-Stage model is that an increase in the number of items in the search array leads to a decrease of the signal-to-noise ratio, and this in itself decreases the possibility of the target being sent to stage 2 and thus being identified. This is what has been emphasized in the SDT-based model. Of course in this model, too,

similarity (and hence, discriminability) plays an important role because the more the discriminability between the target and the distractors, the more the value of d' , and thus the more the possibility that the target will pop out.

The main concern in all these three accounts of visual search, therefore, is the function of identity extraction. Increasing the similarity between the target and the distractors, as well as increasing the number of items in the display, lead to a more difficult identification process for the target. If we postulate that the process of spatial selection, too, becomes more difficult at the same time, one possible conclusion can be that in these three accounts of visual search, spatial selection and identity extraction are not considered as two separate functions, just as is the case in the following account.

D) Not separable functions

Green's Account

This account (Green, 1991; Green, 1992) emphasizes that detection, localization, and identification are virtually the same process. By trying to correct some of methodological problems of the previous experiments, this study tries to solve the conflict between FIT and the study of Sagi and Julesz (1985a, b). In FIT, as discussed before, identification of features occurs before their localization, and it is only with focal attention that the location of the feature can be processed as well. In Sagi and Julesz's account, however, a defect in the feature gradient is detected first, and then a signal from that location will call for attention to help identify the target. Green argues that, for example, localization task in Sagi and Julesz's study was relative. Namely, in that study, the task was to say if the three targets formed a right triangle. Also, Green believes that Sagi and Julesz's identification task was really a discrimination task, which is a

combination of identifying the target first, and then comparing the targets. Therefore, in two experiments, he tries to compare detection and identification first, and then to compare absolute – as opposed to relative – localization with detection. He attains no difference in the performance of his two subjects in those experiments.

Spatial selection and identity extraction in Green’s account:

Green’s (1991; 1992) account of visual search can be summarized as follows: “1) feature modules are directly connected to one another, 2) features and their locations are represented together, 3) feature detection and integration are not distinct processing stages, and 4) no executive control process, such as focal attention, is needed to integrate features” (Green, 1991, p. 388). Yet put more simply, detection, localization, and identification are not separable functions. The role of attention, however, is not clearly explained in this view.

Summary: Spatial Selection and Identity Extraction in Theories of Visual Search

As discussed above, some theories make a distinction between the processes of spatial selection and identity extraction (although the extent to which this distinction is made varies), and some of them do not make this distinction. In FIT, the first step in the visual processing of a stimulus is an analysis of its basic features such as colour, orientation, luminance, or direction of movement. This is a parallel stage throughout the visual field; that is, all stimuli simultaneously enter the visual system and are broken down into their fundamental attributes by feature analyzers. In addition to being parallel, this stage is also pre-attentive – there is no need for a higher level cognitive process such as attention to intervene for this process to take place. Hence, so far, all the visual system “knows” about the stimuli is their basic features – other information such as their location

or identity must wait until the next stage of processing. That is why in FIT, the features are described as free-floating in the first pre-attentive stage. To gain access to any information about the location of the stimuli, attention is needed. In summary, FIT distinguishes between the identification of features and localizing them and hypothesizes that, at least in a feature search, the process of identification precedes the process of localization of that feature. To localize a feature or to identify a conjunction of features, however, focal attention is required. This means that in FIT spatial selection and identity extraction are distinct functions. In feature search, they are separable because they function independently. In conjunction search, however, they might not be totally separable because localization is the necessary step for identification of the target.

What was said for conjunction search in FIT is also true for the next two accounts in which spatial selection always occurs prior to identity extraction. Namely, in these two accounts although spatial selection and identity extraction are considered to be two distinct functions, they might not be quite separable. In one of these studies (Sagi & Julesz, 1985a), orientation was tested as a basic feature. The search array consisted of oblique line segments as distractors, and either vertical or horizontal line segments as targets. When observers were asked to report the number of both vertical and horizontal line segments regardless of their orientation (detection task), the observers seemed to carry out the search in a parallel manner, showing a flat search slope. When, on the other hand, they were asked to report whether all the targets had the same orientation or whether one of them was oriented differently (discrimination task), the observers showed a steep search slope and therefore, it seemed as if they carried out this task serially. The conclusion was that attention is needed for discrimination of such basic feature as

orientation, even without being in conjunction with any other features. When there is a discontinuity in the feature gradient, this discontinuity is detected first, and then, if necessary, discrimination can take place using attentional processes (but see Di Lollo, Kawahara, Zuvic, & Visser, 2001). In this account, detecting a discontinuity in the feature gradient is equivalent to localizing that discontinuity whereas discriminating the orientation is equivalent to identifying the stimuli.

In the other account in which it is suggested that spatial selection has priority over identity extraction (Johnston & Pashler, 1990) it is argued that Sagi & Julesz's (1985a) results can be explained in terms of a "perceptual flow field". Namely, the homogeneous array of oblique line segments that they used in their study can be considered to produce a flow. A "break" in that flow can be perceived and, therefore, treated by the visual system as a visual feature. In this study, unlike in Sagi and Julesz's study, the distractors did not form a homogeneous background. Thus, a difference signal that results from a "break" in the array of items' gradient cannot explain the parallel search.

In Sagi and Julesz's (1985a) model, detecting and discriminating (or localizing and identifying) are theoretically quite distinct from one another. They argue that a difference signal, based on the location of the break in the gradient, is the first signal that is perceived. Therefore, regardless of the identity of the target, its location is perceived at the first stage. Consequently, if the task is just to report the location of the target (or just to detect the presence of the feature target), it can be done in parallel and with no set size effect. If, on the other hand, the task is to report the identity of the target, then attention is needed and as a result, the search will be carried out serially. In Johnston and Pashler's (1990) model, however, although theoretically there could not be any identification

without localization, these two processes are not completely separate. In their data, only in 10% of trials did they observe that the participants could report the location of the target without being able to identify it. In their view, processing the identity of a feature target, as well as its location, takes place pre-attentively, and “what is deferred until servicing of the interrupt signal is only the transfer of the feature identity to central processes, not its computation” (p. 854). Considering the parting of the “dorsal” and “ventral” pathways, Johnston and Pashler argue that their findings could have either of two meanings: a) perhaps feature analysis takes place before the two pathways separate, or b) the task needs some location information that can be obtained only from the temporal lobe, because information there is topological.

While processes such as gradient discontinuity and feature analysis are considered here as potential bases for parallel processing, to avoid any confusion, it is worth mentioning that parallel search and effortless texture segmentation are not necessarily the same process. It has been demonstrated (Wolfe, 1992) that a search display can lead to either a parallel or a serial search (here meaning a flat or steep search slope) independently from showing an effortless or effortful segmentation at the same time.

In Guided Search and Dimensional Weighting accounts, too, spatial selection, when occurs, is considered to take place before identity extraction. The guiding signal in Guided Search is a sum of different bottom-up and top-down factors. Therefore, when the guiding signal is available, it will be considered before the identification stage. In describing this process, the Dimensional Weighting account adheres to the account given by the Guided Search model (and conjunction search in FIT). Thus, in terms of

separability of spatial selection and identity extraction, they join the same category as Sagi and Julesz's and Johnston and Pashler's.

Finally, in Green's (1992) account of visual search, spatial selection and identity extraction are considered to occur at the same time and thus serve the same function. Three other accounts of visual search – the Two-Stage model, the Resemblance account, and the SDT-based account – can join Green's account in this category, since they say nothing about the spatial selection process and also they have some very essential aspects in common. These aspects were discussed in Category C in the Theories of Visual Search section.

The comparison of different accounts of visual search shows the vast controversy about the issue of separability of search functions, from independency, to being distinct but not quite separable, and to being totally inseparable. As mentioned in the introduction, however, there are anatomical, neurological, and behavioural evidence to support the possibility that the two function of visual search may actually be separable. In the next section, this possibility is more deeply discussed in terms of two major visual pathways: dorsal versus ventral.

Magnocellular versus Parvocellular

Ever since the idea of two separate visual pathways was proposed (Ungerleider & Mishkin, 1982), it has fueled a great deal of research. The first proposal was that there are two separate major pathways originating from the visual cortex area V1 (for a review see Calloway, 1998). The ventral stream is mostly involved in identification tasks that deal with features such as form, colour, and (high) spatial frequency (Livingstone & Hubel, 1988). This pathway is mainly driven by parvocellular neurons, although

magnocellular neurons also contribute, but to a lesser extent (Ferrera, Nealey, & Maunsell, 1992). Separation of parvocellular and magnocellular neurons starts at the retina, with the parvocellular ganglion cells almost exclusively covering the foveal area, and the number of magnocellular ganglion cells increasing towards the periphery. Parvocellular neurons have smaller receptive fields and slower conduction rates than do magnocellular neurons. These attributes make them ideal for processing more identity-related characteristics such as colour and form. In contrast to the ventral stream, the dorsal stream is mostly involved in space related tasks such as motion and depth perception. This pathway is largely driven by magnocellular neurons, which have larger receptive fields and faster conduction rates (Lamme & Roelfsema, 2000; Nowak & Bullier, 1997; Schmolesky et al., 1998; Vidyasagar, 1999).

A major revision of the original two-system idea took place when Goodale and Milner (1992; Goodale, Milner, Jakobson, & Carey, 1991; Milner & Goodale, 1995) suggested that the ventral pathway is mostly involved in object identification tasks where consciousness plays an important role. The dorsal pathway, they proposed, is mostly involved in spatial action related tasks in which consciousness might not be necessary (Liu, Healey, & Enns, 2003).

In the context of visual search, and in light of the dual-system theory of vision, it seems appropriate to propose two separable components for visual search: if there is a location cue that can be detected, the magno system can take advantage of it (see Vidyasagar, 1999). Given its fast neural transfer rate, in addition to its main responsibility in dealing with spatial information, the dorsal stream is an ideal candidate for this task. The parvo system, on the other hand, taking advantage of its better

resolution for high spatial frequencies and other identity related aspects, is the best candidate for carrying out identity extraction. In summary, in suggesting that spatial selection and identity extraction are separable processes, the existence of two fairly independent neural pathways, one of which seems ideally suited to processing location information and one that seems better suited to identity extraction, is a critical piece of evidence.

The Human Attentional Network Model

Another source of support for the separability of spatial selection and identity extraction is a well-researched account of human attention which suggests that location and identity information are processed in two separate neural networks (Posner & Petersen, 1990; Posner, Sheese, Odludaş, & Tang, 2006). The Human Attentional Network account is ideally suited for understanding the processes of visual search in that it provides an account of how attention can be moved in the visual field, a process that is clearly required when finding a target among distractors. In providing this explanation, it invokes a “spotlight” metaphor of attention. This single spotlight makes it difficult to process two areas which do not neighbour each other, which in turn necessitates a moving of the spotlight around the visual field. Also, as the distance between the item being processed and the center of the spotlight increases, the extent to which that item is processed decreases. Finally, shifts of the spotlight can take place with a certain velocity and thus, the intermediate areas in the shift path receive the benefits of the spotlight (Briand & Klein, 1987; but see Sperling & Weichselgartner, 1995).

According to this theory, attention, as indexed by enhanced processing of a stimulus or location, is instantiated in the brain as an extensive network of anatomical areas.

Smaller sub-networks of this overall attention network are responsible for the various functional sub-components of attention. The Human Attentional Network Model suggests that although the processing involved in any cognitive task is distributed throughout the brain in extensive networks, all tasks can be subdivided into smaller tasks which are completed in specialized neural areas. Attention, Posner argues, can be profitably understood and studied as a series of connected networks, hence the name of his model, the Human Attentional Network model (Posner & Petersen, 1990). He suggests that a task such as finding and reporting a target item consists of three separate sub-tasks that call on three separate attentional networks: the *posterior attention network* which is responsible for spatial shifts of attention, the *anterior or ventral attention network* which is responsible for identifying objects, and the *executive network* which is responsible for coordinating and controlling the other two systems.

The first network, the posterior attention network, underlies spatial shifts of attention. Consider for a moment the steps that might be involved in shifting attention. Imagine that you are asked to complete a task wherein two targets appear one after another in different spatial locations on a computer screen, and your task is to identify the two targets as quickly and accurately as possible. In this case, the two targets are lines which are tilted slightly to the left or the right, and you must indicate the direction of the tilt as quickly as possible. Since this is a relatively difficult task, in order to accurately identify the targets, you will have to shift your attention from the first target to the second target when it appears. Posner argues that there are three separate stages involved in this shift of attention. First, after the first target has been processed, attention must be disengaged from that target so that it may be shifted to the second target. Then, the

actual shift to the second target's location must be completed. Finally, attention must be engaged on the new target so that it can be processed and identified. In other words, an attentional shift has three components: disengage, shift, and engage.

It is well-established that neurons discharge at a greater rate to a stimulus when the location of that stimulus is attended (see Posner & Petersen, 1990 for an overview). Given this, evidence of attention can be seen in neural areas that show a modulation of their activity when attention is deployed and the areas that show such modulation can be pinpointed through single cell recordings in monkeys, neuroimaging in normal humans, and lesion studies. From these sources, Posner concludes that three separate neural areas underlie attention shifts: the parietal lobe, the superior colliculus, and the pulvinar nucleus of the thalamus. Although damage to any of these three areas leads to deficits in attention shifts, the exact nature of the deficit is distinctly different depending on which brain area was damaged. Specifically, damage to the parietal lobe leads to deficits in disengaging attention from the current object/location of attention (Posner, 1980; Posner, 1992; Posner, Walker, Friedrich, & Rafal, 1984), damage to the superior colliculus results in deficits in the actual shifting of attention from one object or location to another (Posner, 1992), while damage to the pulvinar causes an inability to engage attention at a new object or location (LaBerge & Buchsbaum, 1988; Posner, 1992). Posner provides considerable evidence that these three different brain areas underlie the three different components of attention shifts.

The second network that Posner proposes is the anterior or ventral attention network. This network is concerned primarily with the identification of objects and the semantic processing of stimuli. It is centered in the left lateral prefrontal cortex, the

anterior cingulate gyrus in the frontal midline, and the temporal lobe. Posner's third and final network is the executive network, which is involved in the resolution of conflict between neural systems and regulating thoughts and feelings (Posner, Sheese, Odludaş, & Tang, 2006; Fan, McCandliss, Fossella, Flombaum, & Posner, 2005) – a task that is mostly carried out in the prefrontal cortex.

There has been a great deal of research in support of the distinction that the Human Attentional Network model makes between the ventral and the posterior attention networks (see Posner & Petersen, 1990 for an overview; Posner, Sheese, Odludaş, & Tang, 2006). Since the model proposes separate but interconnected neural networks that underlie the processing of spatial and identity information, it could also be extrapolated to suggest that the two features of visual search, namely spatial selection and identity extraction, are also separable, albeit interconnected processes.

Theories of visual search and testing separability of search functions

So far, a variety of anatomical, neurological, and behavioural evidence has been presented to support the possible separation of spatial selection and identity extraction. Furthermore, the controversy among different accounts of visual search as to whether or not spatial selection and identity extraction are separable features was discussed in some detail. The lack of consensus among these theories is a clear call for further research. One possible reason for the lack of consensus is that perhaps the different accounts of visual search did not employ the right tool or methodology to answer this question. The factors that are typically manipulated in the research supporting these various theories are the number of items in the display, the similarity between the target and the distractors or among the distractors, the defining target feature being only a single or a conjunction of

features, the density of the items in the display, and the defining target feature being known or unknown in advance. It is possible, however, that these manipulations do not affect, unambiguously and exclusively, only spatial selection or only identity extraction. For instance, while varying the number of items in the display can affect the spatial selection function, it is also possible for it to increase the noise in the display – especially when target-distractor similarity is high – and thus to influence the function of identity extraction as well. This is also true for most of the other factors that have served as independent measures in visual search studies.

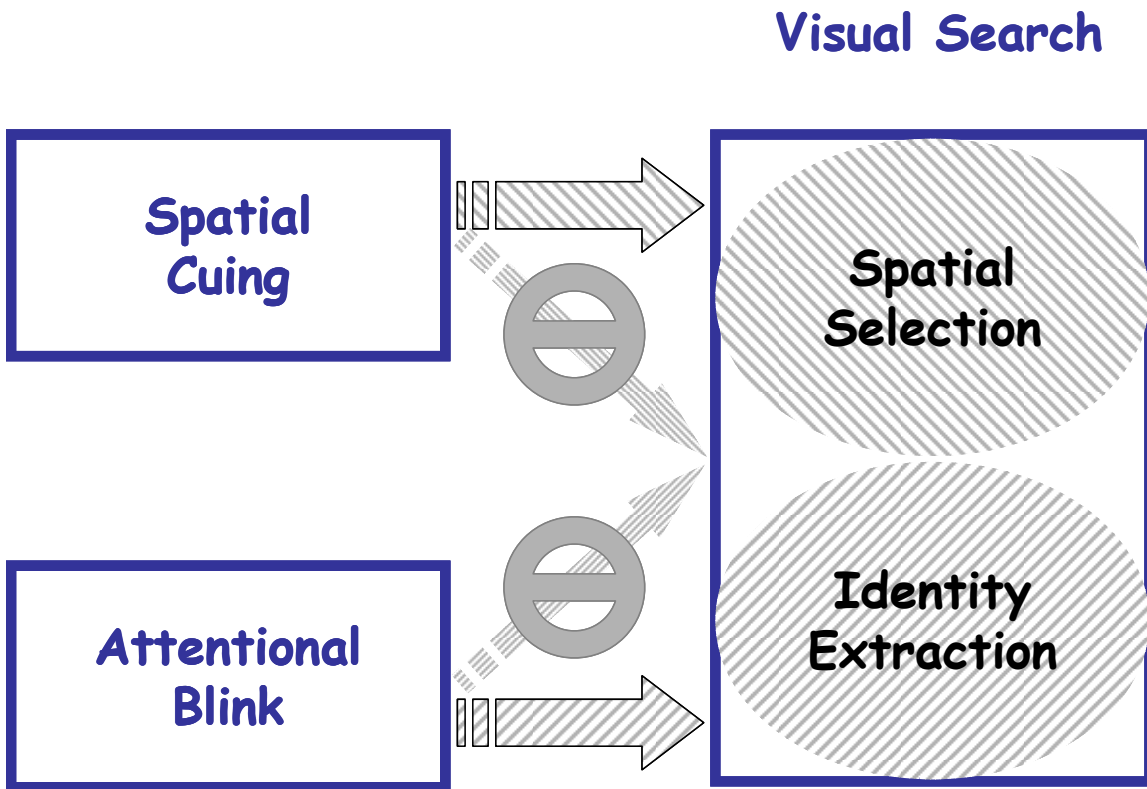
One plausible way to manipulate separately those factors that influence spatial selection from factors that influence identity extraction is to influence either of the functions of search from outside the search paradigm. Throughout this dissertation, this has been done by finding factors that can affect only one of the two functions. These factors are then inserted in a dual-task paradigm. A dual-task paradigm is an excellent tool for this purpose: putting the search task as the second task allows it to be affected by factors that precede it, for example, in the first task. Having been affected by only one factor, if spatial selection and identity extraction co-vary, it would mean that they do not operate independently. If, on the other hand, affecting one function does not affect the other function, it would be taken as indicating that these two functions are separable (Figure 1.1). This, therefore, will serve as the operational definition of separability in our experiments.

More specifically, one factor – spatial cueing – is used to affect the efficiency of spatial selection, and another factor – inter-target lag between a leading target and the search display within an attentional-blink paradigm – is used to affect the efficiency of

identity extraction. The attentional blink (AB) is an impairment in the identification of the second of two targets when they are presented sequentially and shortly after one another. The AB is said to be the result of a delay in the processing of the second target while the system is busy processing the first target. This delay makes the second target vulnerable to masking or decay.

In all the experiments, efficiency of performance will be measured by response accuracy or by the critical exposure duration (or the critical inter-stimulus interval) required for a criterial level of performance. If spatial cueing is shown to affect, or to be affected by the AB, this would be taken as evidence against separability of search functions. If, on the other hand, spatial cueing and the AB are shown to have orthogonal effects, it will be concluded that spatial selection and identity extraction are independent processes. Full descriptions of the rationale behind this approach and of the procedural details employed in the experiments are presented in each chapter that follows this introduction.

Figure 1.1. The basic methodology followed throughout this dissertation to investigate the separability of spatial selection and identity extraction.



The results from these experiments will therefore have direct implications for our understanding of visual search, its components, and whether they are independent and separable functions. Specifically, as noted above, the experimental outcomes will offer useful constraints for theories of visual search, and will provide basic information for practical applications. The results, however, are not necessarily limited to visual search, since visual search is only a suitable instance of how spatial selection and identity extraction can work in the same context. As will be presented in the following experiments, separability of these two functions is demonstrated in other contexts, too.

This demonstration generalizes the conclusions of this dissertation beyond visual search to any context in which spatial selection and identity extraction are at work.

Conclusion

Different accounts of visual search do not agree on the separability of the two functions of visual search. Some suggest that these two functions are independent, while others suggest that even though they might be distinct functions, they are not completely separable. Yet some other accounts argue that these two functions are virtually the same. There is, however, evidence to support the separability of these two functions.

Anatomically, two separate visual pathways – dorsal versus ventral pathway – are responsible for spatial tasks versus identification tasks. The dorsal pathway consists of magnocellular neurons, whereas the ventral pathway consists mostly of parvocellular neurons. These two types of neurons separate early in the retina and follow different pathways through the brain. Neurological findings, too, support this separation in function. Damage to the dorsal stream leads to optic ataxia, while damage to the ventral stream results in visual agnosia. There are also behavioural studies that show, for example, that object identification can be interrupted by planning an action (a ventral-stream task) but not by the on-line control of the action (a dorsal-stream task).

Further support for this idea comes from some accounts of visual attention. In the Human Attentional Network model, for instance, three separate networks perform the function of attention. In this model, spatial selection is carried out in the dorsal attention network while identity extraction is performed in the anterior/ventral attention network.

The controversy about the separability of spatial selection and identity extraction in visual search may have arisen from the specific methodology that has been adopted by

researchers investigating this issue. The key may be that the specific factor(s) which have been manipulated as the independent measure in the research so far could potentially affect *both* spatial selection and identity extraction, making it impossible to dissociate them. A more appropriate approach, therefore, would be to adopt a methodology in which it is at least theoretically possible to influence the two functions of search independently. The results will be generalized beyond visual search when they are demonstrated in a different context.

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CHAPTER 2:

Spatial Selection is Separable from Identity Extraction in Visual Search²

In a typical visual search experiment, observers are required to find a target object that is randomly located among several other distractor objects. There are two tasks that usually confront the observer in the course of visual search: locating the target within the search display, and extracting the target's identity. Considerable theorizing in the past has been devoted to the question of the temporal order of these two operations, with some arguing for identity extraction prior to spatial localization (e.g., Treisman & Gelade, 1980), others arguing for spatial localization prior to identity extraction (e.g., Julesz, 1984), and still others positing the inherent inseparability of these two mental operations (e.g., Green, 1991; 1992). However, here we address an even more fundamental question – one that has not been examined systematically to date – namely, whether spatial selection and identity extraction are dissociable functions.

In our view, the question of *dissociability* (or equivalently *separability*) of these two mental operations has logical priority over the question of whether one of these operations must be performed prior to the other. If the operations are separable, then the relative ordering of the operations can be explored as a secondary question. However, if these operations are inseparable, because they both rely on common cognitive resources, then the question of relative ordering becomes moot. In the sections that follow, we will briefly review past theoretical and empirical contributions to this question, before turning to a series of three experiments that examine this question in a new way.

² A version of this chapter has been submitted for publication. Ghorashi, S., Enns, J. T., Klein, R. M., & Di Lollo, V. Spatial selection is separable from identity extraction in visual search.

Theories of visual search certainly differ in the emphasis they place on the processes of spatial selection versus identity extraction. For example, the most influential framework for interpreting visual search has been *Feature Integration Theory* (Treisman & Gelade, 1980), which holds that visual features such as colour and shape are initially registered in separate topographically organized regions of the brain. In order to identify any particular conjunction of features as belonging to the same object, information from remote brain regions must be combined (the metaphor of attention as “glue” was used in early papers on FIT, the term “binding” is used in more recent papers). The integration of features requires a master map of spatial locations to which all feature maps have access. Moreover, feature integration is inherently a serial operation; it can only be done one location (or object) at a time. According to FIT, visual search tasks are slow and effortful when feature integration must be performed for each item in the display until the target is found. Search tasks become faster and easier when the target item can be identified on the basis of unique activity in a single feature map. No linking of different feature maps is required and so the master map can be consulted directly.

Although Feature Integration Theory has undergone several modifications since its inception (Treisman, 1988; Treisman & Gormican, 1988; Treisman & Sato, 1990), it still proposes that the limiting factor on search efficiency in this account is the feature integration process, not the step of spatially localizing the conjoined features in the search display. Note that the main theoretical competitors to this theory also place more emphasis on identity extraction than on spatial localization. For example, *resemblance theory* (Duncan & Humphreys, 1989) proposes the similarity relations among the display items limit search efficiency, both similarity relations of targets to distractors and those

among the distractors. Wolfe's (1994; 2006) *guided search theory* also highlights inter-item relationships, though it does so through the complexity of the interactions among feature maps that are needed to define a target as distinct from the distractors.

In contrast to this emphasis on identity extraction, other theories of visual search have placed greater emphasis on the control of an attentional spotlight or zoom lens that is able to privilege processing within a limited region of space (Eriksen & Yeh, 1985; Posner, 1980). The most complete theory of this kind is *texton theory* (Julesz, 1984; Sagi & Julesz, 1985a, b) which holds that target identification occurs only after an initial stage of processing in which the visual image has been analyzed for spatially localized discontinuities in simple visual features. Discontinuity localization is said to be a parallel process, though its efficiency is still a function of strength of the signal that is derived from the discontinuity at any given location. Furthermore, registration of features in a given location is a serial process, leading to the prediction that the location of spatial discontinuity in a display will invariably occur prior to the identification of their featural properties.

In support of this theory, Sagi and Julesz (1985a, b) reported a dissociation between the detection and discrimination of orientation-defined targets. Specifically, a target detection task (involving only discontinuity localization for each item) yielded no differences in search time as a function of display size, but a discrimination task with the same displays (involving item identification) increased as the number of candidate items increased. In a separate experiment, the detection task was compared to a localization task in which observers had to indicate the spatial configuration of target items. These two tasks yielded overlapping psychometric curves, consistent with the idea that spatial

discontinuities can be detected and localized in parallel, but that the identification of a target in terms of its non-spatial features can only be done serially. Yet this interpretation has not gone unchallenged. Di Lollo, Kawahara, Zuvic, and Visser (2001) pointed out the detection task of Sagi and Julesz (1985a, b) involved a single mental operation (detect local spatial discontinuities), whereas the discrimination task involved two operations (detect discontinuities before identifying feature differences). After the tasks and operations had been systematically disentangled, Di Lollo et al. concluded that the relative inefficiency of the discrimination task was better characterized as dual-task interference.

There are anatomical and neurological reasons to suspect that spatial selection and identity extraction may be separable functions. When two major pathways were recognized in the visual system (Ungerleider & Mishkin, 1982), they were described as underlying two separate functions. The dorsal and the ventral pathways were called “Where” and “What” pathways, respectively, because space-related processes such as motion and depth perception were shown to be carried out in the dorsal stream, whereas object identification was demonstrated to be the main engagement of the ventral stream. These two pathways involve two separate systems of neurons: magnocellular and parvocellular. Magnocellular neurons have relatively larger receptive fields and faster conduction rates than do parvocellular neurons. These attributes make them ideal for spatial selection tasks. In contrast, the ventral pathway consists mainly of parvocellular neurons, which have smaller receptive fields and slower conduction rates. These make the ventral pathway an ideal candidate for processing more identity-related characteristics such as colour and form. It does not seem implausible, therefore, to map the separability

of spatial selection and identity extraction onto the dissociation of magnocellular and parvocellular systems – a dissociation that starts as early as in the retina.

Some of the strongest empirical evidence favouring the separability of spatial localization and item identification in visual search has come from the neuropsychological literature. For example, patients with optic ataxia (Bálint, 1909) typically have damage in the superior portion of the posterior parietal cortex (dorsal stream). Functionally, they are able to identify the non-spatial features of items without being able to successfully localize the positions of these features in space (Goodale, Milner, Jakobson, & Carey, 1991; Perenin & Vighetto, 1988). Conversely, other patients have been reported (Milner et al., 1991) who had damage to the ventrolateral regions of the occipital lobe or to the inferior temporal lobe (ventral stream). These patients usually show symptoms of visual agnosia in which they are unable to identify or describe attributes of visually presented objects, although they can use those objects in actions.

Similarly, behavioral studies with neurologically-intact subjects have also provided hints that spatial selection and identity extraction may be separable functions. It has been shown, for instance, that while the identification of an object interferes with the planning of reaching for another object (a ventral-pathway task), it does not interfere with the visually guided control necessary for completing the action (a dorsal-pathway task; Liu, Chua, & Enns, 2008). Also, there is evidence to support the occurrence of spatial selection without identity extraction for the target (Atkinson & Braddick, 1989; Ghorashi, Jefferies, Kawahara, & Watanabe, 2008).

There is also evidence for the separability of spatial selection and identity extraction in developmental studies. Trick and Enns (1998) have shown that voluntary

movement of attention (spatial selection) and feature integration (identifying the target) have different trajectories over the lifespan. They displayed either a target that was defined by a single feature or a target that was defined by a conjunction of two features. They presented the target either as a single item in random locations, or as a target among distractors. Results showed that feature binding reaches its asymptote at a relatively earlier age in life, and then stays at that level, whereas voluntary movement of spatial attention follows a U-shaped pattern of performance across the lifespan. Namely, it matures at a later age than feature binding does, and declines in senior adulthood.

Finally, some electrophysiological studies suggest that the dissociation of spatial selection and identity extraction can be shown at least during the earlier stages of visual processing. In an event related potential (ERP) study, Handy, Green, Klein, and Mangun (2001) set out to test whether all the items that are included in the spotlight of attention benefit from performance facilitation. Building on a previous study by Klein (1980), they used an arrow as a spatial cue that indicated the most likely location of the upcoming target (a grating), and a letter cue (V or H) to indicate whether the orientation of the upcoming grating target was vertical or horizontal. The observers were instructed to press two different keys depending on the orientation of the target. They replicated Klein's results showing that when response times are measured as the dependent variable, unlike the expected (validly-cued) targets, the unexpected (invalidly-cued) targets do not benefit from the advance knowledge of location even when presented in the expected location. This was not the case, however, in Handy et al.'s next experiment, in which the amplitude of the early ERPs components (the lateral occipital P1 and N1 and the parietal N1) were measured. Namely, the amplitude of the early ERPs components increased

when the location of the target was expected, regardless of whether or not the identity (orientation) of the target was expected.

Despite all these indications, however, the implicit assumption of separability of spatial selection and identity extraction cannot be verified against experimental data. This is because in most visual search studies, factors that influence both spatial selection and identity processing have invariably been manipulated concurrently. For example, increasing the set-size in a search display will impair spatial selectivity by increasing the number of potential target locations. Yet the same manipulation will also impair identity extraction by decreasing the signal-to-noise ratio. Thus, the extant empirical evidence is inadequate for resolving the issue of separability.

In the present work, the question of separability is addressed in a series of behavioural experiments in which two paradigms are used to influence the efficiency of spatial selection and identity extraction separately. The two paradigms have been commonly used in attentional studies: exogenous spatial cueing, and the attentional blink.

Exogenous spatial cues (e.g., a bright dot displayed briefly at the expected location of an ensuing target) have been used to study the deployment of attention to specific locations in a visual display (e.g., Eriksen & Hoffman, 1972). This is a manipulation that obviously influences spatial selection. The attentional blink (AB) is an impairment in the identification accuracy of the second of two targets inserted in a stream of distractors displayed in rapid serial visual presentation (RSVP). This second-target deficit is obtained when the temporal lag between the two targets is less than about 500 ms (Raymond, Shapiro, & Arnell, 1992). The AB is generally regarded as a high-level phenomenon that interferes with the process of identity extraction (Chun & Potter, 1995;

Jolicœur & Dell'Acqua, 1998). Moreover, the AB has been shown not to interfere with the process of spatial selection (Ghorashi, Di Lollo, & Klein, 2007).

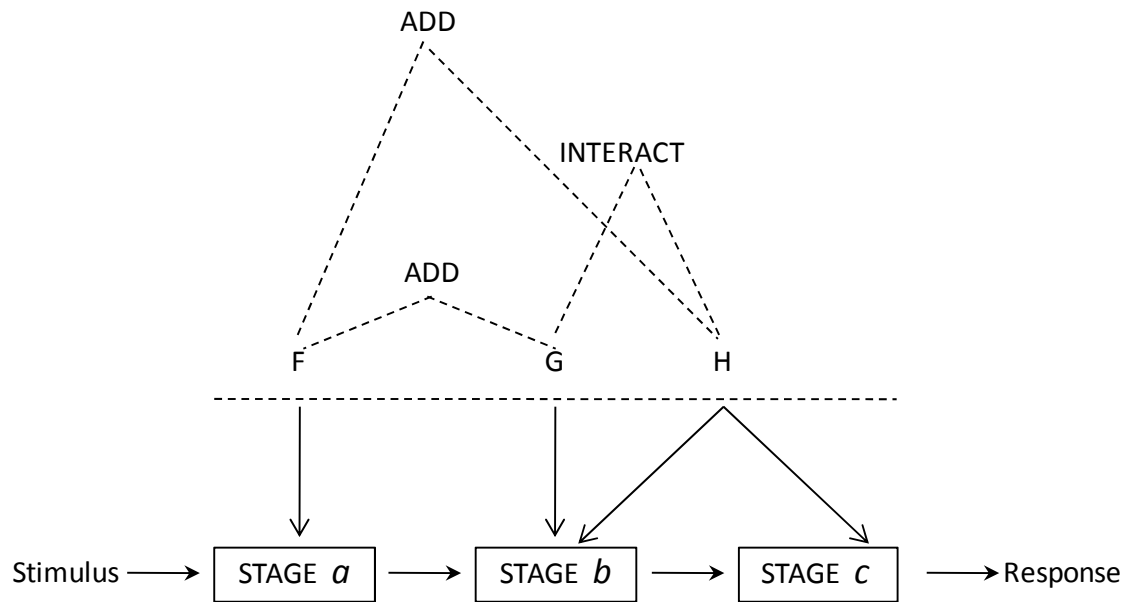
In examining the separability of spatial selection and identity extraction in visual search, we adopt additive-factors logic in which it is assumed that processing is carried out in a series of non-overlapping stages. If two factors influence independent stages of processing, they will have additive effects on the dependent measure. Conversely, whenever additivity is found, the underlying stages of processing can be assumed to be independent (Sternberg, 1969). If, on the other hand, at least one of the factors influences both stages, as evidenced by an interaction between the effects of the two factors on the dependent measure, then the underlying stages of processing are interpreted as not independent.

Sternberg (1969, p.287) expressed the relationship between the additive effects of two factors and the idea of independence of processing stages, as follows:

Suppose, for example, that we wish to test the following hypothesis, H1: stimulus encoding and response selection are accomplished by different stages, *a* and *b*. This can be tested only jointly with an additional hypothesis, H2: a particular factor, F, influences stage *a* and not *b*, and a particular factor, G, influences stage *b* and not *a*. If F and G are found to be additive, both hypotheses gain in strength. But the falsity of either H1 or H2 could produce a failure of additivity.

This relationship is illustrated graphically in Figure 2.1, redrawn from Figure 2 in Sternberg (1969).

Figure 2.1 (redrawn from Sternberg, 1969, Figure 2). “Example of an arrangement of stages (a, b, and c) and factors (F, G, and H). Below the horizontal line are shown three hypothetical stages between stimulus and response. Horizontal arrows represent inputs and outputs of stages; time proceeds from left to right ... Arrows are drawn from factors to the stages assumed to be influenced by those factors.” (Sternberg, 1969, p. 281)



The use of additive-factors logic in the present experiments, therefore, allows us to test two hypotheses: a) that spatial cueing affects principally the process of spatial selection, and the AB affects identity extraction, and b) that spatial selection and identity extraction are two independent stages of processing. If spatial cueing and the AB show additive effects on the response measure, they can be regarded as affecting non-overlapping stages of processing independently. It can then be concluded that spatial selection and identity extraction are separable processes. If, on the other hand, the effect of cueing is found to interact with the AB, it can be concluded that spatial selection and identity extraction are not entirely independent stages of processing but have at least

some stages of processing in common. Thus, the use of separate psychophysical tasks permits an operational definition of the separability of the two functions.

Experiment 2.1

Experiment 2.1 was designed to examine the separability of spatial selection and identity extraction in a visual-search task. This was done by manipulating the two factors independently within the same experiment. The identity-extraction function was manipulated by varying the inter-target lag in an AB paradigm. The displays consisted of an RSVP stream of distractors (black letters) containing two targets. The first target was a white letter to be identified; the second target (a "T" tilted left or right) was inserted in a circular search array of 11 rotated "L"s. The spatial-selection function was manipulated by the presence or absence of a temporally leading spatial cue (a dot) presented briefly at the location of the upcoming second target. The cue was present in one block of trials and absent in another block.

It is known that cueing the location of an upcoming target leads to substantial benefits (e.g., Colegate, Hoffman, & Eriksen, 1973). On this basis, we expected identification of the second target to be more accurate when it was cued. The critical issue in Experiment 2.1, however, was whether the benefit conferred by spatial cueing was invariant with inter-target lag or whether it varied across lags. Parallel functions for the cued and uncued conditions across lags would be evidence for the separability of spatial selection and identity extraction. Interacting functions, on the other hand, would be evidence of interdependence.

Method

Observers

Twelve undergraduate students at the University of British Columbia participated for course credit. All reported normal or corrected-to-normal vision.

Apparatus and Stimuli

Stimuli were displayed on an NEC AccuSync 70 colour monitor controlled by an IBM-compatible microcomputer. The background was mid-grey and contained a black fixation cross that subtended 0.5° of visual angle at the centre of the screen. The stimuli in the central RSVP stream consisted of black upper-case letters (distractors) and a white upper-case letter (the first target), all subtending 0.6° of visual angle vertically. The search array containing the second target consisted of 11 randomly-rotated "L"s and one tilted "T" (the target). The letters in the search array subtended 0.5° of visual angle vertically. The "T" was tilted 45° either to the left or to the right. The stimuli in the search array were spaced regularly around an imaginary clock face of 2.5° radius, centered at fixation.

Procedure

All displays were viewed from a distance of approximately 60 cm. At the beginning of each trial the fixation cross was presented in the centre of the screen. Observers initiated each trial by pressing the spacebar, at which point the fixation cross disappeared and the RSVP sequence began after a random delay of 400-800 ms. The distractors (black letters) in the RSVP stream were drawn randomly without replacement from the English alphabet excepting Q. Each letter was displayed for 40 ms and was

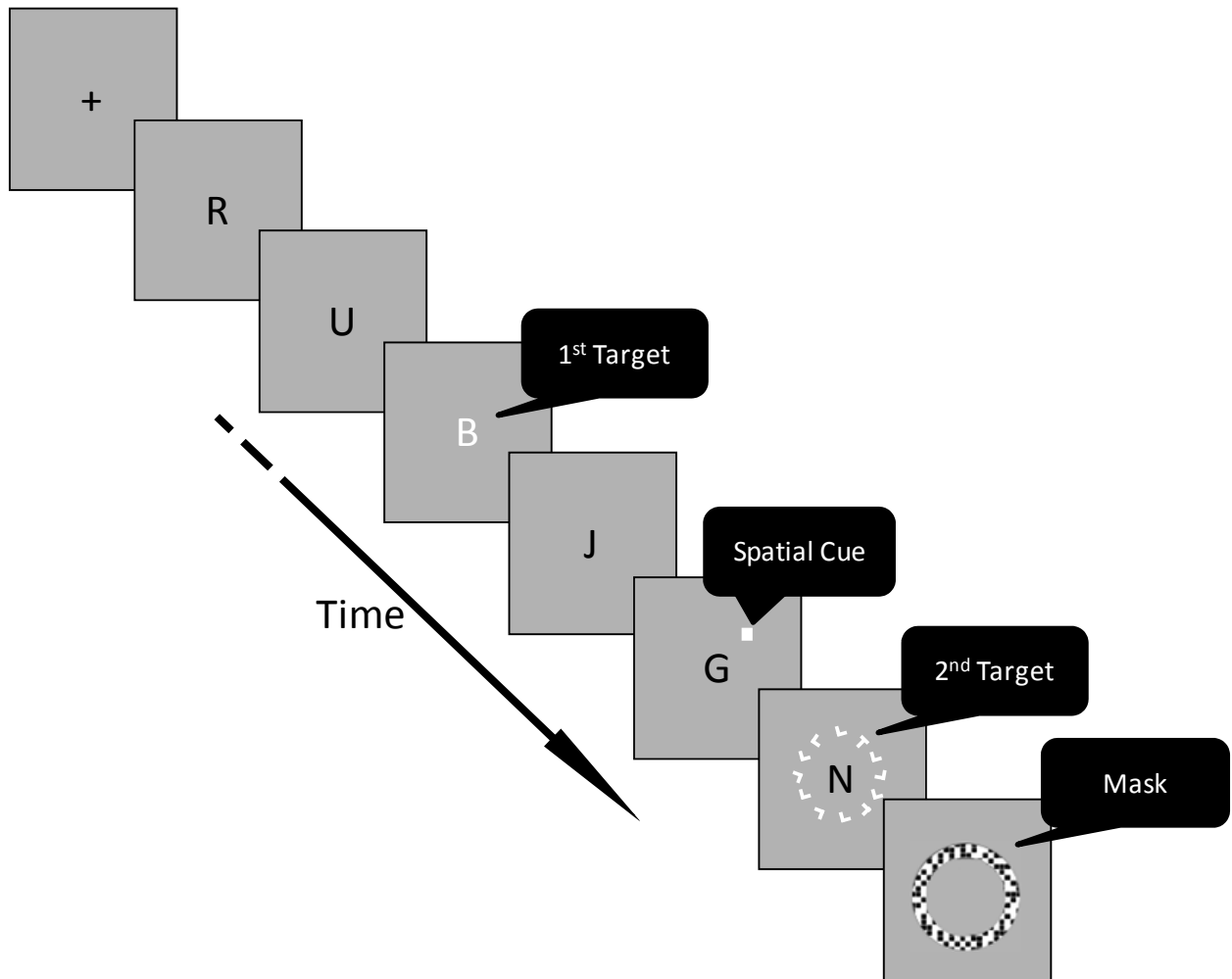
separated from the next letter by an inter-stimulus interval (ISI) of 50 ms, during which the screen was blank. This resulted in a stimulus-onset asynchrony (SOA) of 90 ms between successive items. The first target was preceded in the RSVP stream by between 5 and 10 distractors, at random.

The search array containing the second target was presented at one of three inter-target lags: Lag 1 (in the frame directly following the first target), Lag 3 (in the third frame after the first target), or Lag 7 (in the seventh frame following the first target). At Lags 3 and 7, distractors continued to be presented throughout the inter-target lag. There were two blocks of 156 trials each, counterbalanced across observers. In the Cue block, a spatial cue – a small white dot – was presented for 40 ms in the RSVP frame preceding the search array, in the location at which the tilted T (the target) in the search array would subsequently appear. Thus the SOA between the cue and the target was 90 ms. The No-Cue block was the same as the Cue block except that the cue was not presented. The observers were instructed to take advantage of the spatial information provided by the cue. In brief, the design of Experiment 2.1 was a 2 (Cue: present or absent) x 3 (Lags: 1, 3, 7) within-subject factorial.

The circular search array containing the second target was displayed for 180 ms and was followed immediately by a 180-ms doughnut-shape mask that completely covered the search array. The pixels inside the mask were randomly coloured black or white. The RSVP stream of distractors continued while the search array was displayed. Examples of the stimuli and the sequence of events on any given trial are illustrated in Figure 2.2. At the end of each trial, observers identified the first target by pressing the

corresponding key on the keyboard, and then indicated whether the second target was tilted to the left or to the right by pressing the left or the right shift key.

Figure 2.2. Sequence of events on each trial. On this trial, the second target was cued.



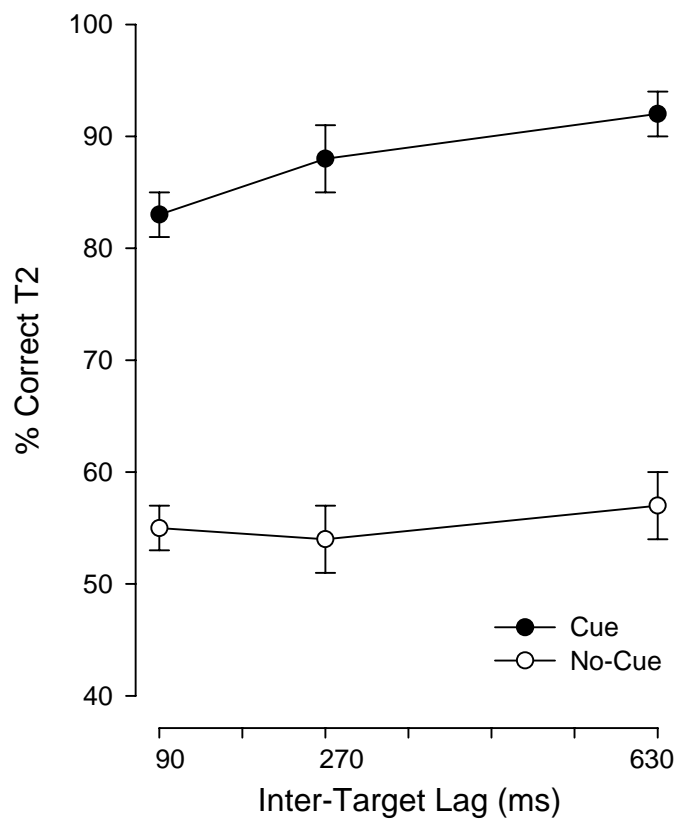
Results and Discussion

In this and all subsequent experiments, estimates of second-target identification were based only on those trials in which the first target was identified correctly. This procedure is commonly used in AB studies on the grounds that, on trials in which the first

target fails to be identified, the source of the error is unknown, thus its effect on second-target processing cannot be evaluated.

Figure 2.3. Results of Experiment 2.1. Bars represent the standard errors of the mean.

T2: Second Target; ms: milliseconds.



The mean percentages of correct responses for the first target, averaged over lags, were 88.9% and 90.7% for the Cue and No-cue conditions, respectively. The mean percentages of correct identification of the second target at each lag are illustrated in Figure 2.3. An analysis of variance (ANOVA) performed on the data in Figure 2.3

comprised two within-subjects factors: Cue (present, absent) and Lag (1, 3, 7). The analysis revealed significant effects of Cue, $F(1, 11) = 99.14, p < .001$, and Lag, $F(2, 22) = 5.99, p = .008$. The interaction effect was not significant, $F(2, 22) = 1.90, p = .174$.

A strong effect of cueing is in evidence in Figure 2.3. On average, the second target was identified about 30% more accurately when its location was cued. Notably, the cue was equally effective whether it was presented during the period of the AB – when stimulus processing is expected to be impaired – or beyond that period. Within the framework of additive-factors logic, this strongly suggests that the mechanisms that mediate the processing of the cue and those that mediate the processing of the second target are non-overlapping. With reference to the main objective of the present work, this means that spatial selection and identity extraction must be regarded as separable processes (also see Appendix 1).

Before reaching a definitive conclusion, however, a possible source of uncertainty must be considered and dismissed. The results in Figure 2.3 show that performance in the No-Cue condition was barely above chance level (50%). It is, therefore, possible that the level to which performance could fall might have been constrained by the floor, thus preventing a possible interaction effect from coming into evidence. This option was examined in Experiment 2.2 in which we used a response measure that was unconstrained by limitations imposed by the response scale.

Experiment 2.2

In Experiment 2.2 the possible constraint imposed by the response scale was obviated by using a dependent measure that avoids that constraint. To this end, we

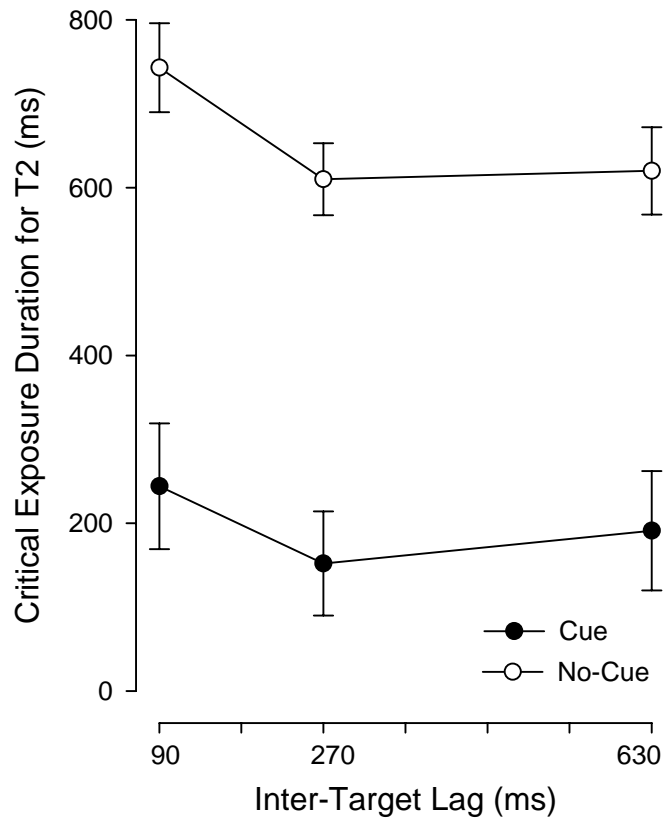
adopted a dynamic threshold-seeking procedure called Parameter Estimation by Sequential Testing (PEST; Taylor & Creelman, 1967). The exposure duration of the search array containing the second target was varied dynamically by PEST, separately for each observer, to converge on a level of 80% correct T2 responses. The dependent measure was the critical exposure duration (DUR_c) at which the observer obtained 80% correct responses. Thus, DUR_c represents the duration of the mask-free interval necessary to achieve the required level of second-target accuracy. Notably, this procedure removed the artificial floor inherent in the response scale used in Experiment 2.1. Twelve new observers served in Experiment 2.2. In all other respects, methods and procedures were the same as in Experiment 2.1.

Results and Discussion

The mean percentages of correct responses for the first target, averaged over lags, were 91.5% and 93.3% for the Cue and No-cue conditions, respectively. The mean DUR_c values for the second target at each lag are illustrated in Figure 2.4. An ANOVA performed on the data in Figure 2.4 comprised two within-subjects factors: Cue (present, absent) and Lag (1, 3, 7). The analysis revealed significant effects of Cue, $F(1, 11) = 137.91, p < .001$, and Lag, $F(2, 22) = 6.87, p = .005$. The interaction effect was not significant, $F < 1$.

Figure 2.4. Results of Experiment 2.2. Bars represent the standard errors of the mean.

T2: Second Target; ms: milliseconds.



As seen in Figure 2.4, much shorter exposure durations (DUR_c) were required when the location of the second target was cued. Also, as was the case in Experiment 2.1, a significant AB deficit was in evidence, with the values of DUR_c decreasing as Lag was increased. The important consideration for the objective of the present work, however, is that the advantage conferred by the spatial cue was invariant with inter-target lag. This pattern of results replicates the outcome of Experiment 2.1 while avoiding the ambiguity caused by a possible floor effect. Considered together, the outcomes of Experiments 2.1 and 2.2 justify the conclusion that spatial selection and identity extraction are separable processes.

Experiment 2.3

Experiment 2.3 was designed to distinguish between stimulus-driven (exogenous) and goal-directed (endogenous) sources of attentional control in Experiments 2.1 and 2.2. As well as differing functionally, the two sources of attentional control are known to be based on distinct neuroanatomical networks (Corbetta & Shulman, 2002). Thus, it is possible that the separability illustrated in Experiments 2.1 and 2.2 could be a characteristic of either or both networks. The 90-ms SOA between the cue and the second target in Experiments 2.1 and 2.2 was clearly sufficient to enable stimulus-driven orienting, with attention being drawn automatically to the location of the target. By the same token, an endogenous source cannot be ruled out because the cue reliably indicated the location of the target, possibly allowing for some degree of volitional control.

To be sure, it is questionable whether the relatively short cue-target SOA was sufficient to activate the goal-directed processes required to re-orient focal attention to the target's location. Nevertheless, we cannot be sure to what extent the separability between spatial selection and identity extraction demonstrated in Experiments 2.1 and 2.2 was attributable to exogenous or endogenous processes. Distinguishing between these two sources of attentional control is also important for theories of attention, some of which hold that the early control of attention is governed solely by exogenous factors (e.g., Theeuwes, 1992; 1993) while others postulate that attentional control is exclusively endogenous (e.g., Folk, Remington, & Johnston, 1992). The two components of attentional control were decoupled in Experiment 2.3 by making the cue entirely non-informative thus eliminating the endogenous component.

Method

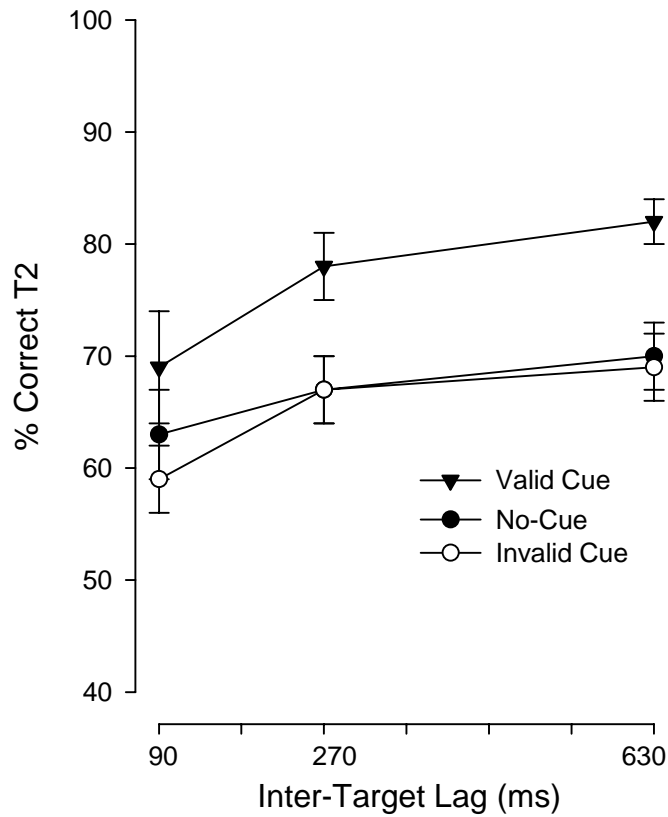
Methods and procedures in Experiment 2.3 were similar to those in Experiment 2.1, except for the following. First, a non-informative spatial cue was used which the observers were instructed to ignore. In practice, the cue appeared equally often in the location of the target as in any of the remaining locations in the search array. Second, the set size was reduced to six items. This was done in order to increase the number of usable validly-cued trials. Third, the design of Experiment 2.3 required that Cue and No-Cue trials be mixed instead of blocked as in Experiment 2.1. Thus, in any given session, there were 1/7 validly-cued trials and 5/7 invalidly-cued trials. In the remaining 1/7 of trials no cue was presented. A new group of 12 observers served for a total of 504 trials.

Results and Discussion

The mean percentages of correct responses for the first target, averaged over lags, were 94.1%, 93.4%, and 94.2% for the No-Cue, Valid-Cue, and Invalid-Cue conditions, respectively. The mean percentages of correct identification of the second target at each lag are illustrated in Figure 2.5, separately for the three cueing conditions. An ANOVA performed on the data in Figure 2.5 comprised two within-subjects factors: Cue (absent, valid, invalid) and Lag (1, 3, 7). The analysis revealed significant effects of Cue, $F(2, 22) = 17.73, p < .001$, and Lag, $F(2, 22) = 24.81, p < .001$. The interaction effect was not significant, $F < 1$.

Figure 2.5. Results of Experiment 2.3. Bars represent the standard errors of the mean.

T2: Second Target; ms: milliseconds.



The pattern of results in Experiment 2.3 mirrors that in Experiment 2.1. Accuracy of second-target identification was higher in the validly-cued condition than in either the invalidly-cued or uncued conditions. Importantly, the facilitation conferred by a valid cue was invariant with lag. Because goal-directed factors in attentional control were ruled out in Experiment 2.3, we can conclude that the effect of exogenous spatial cueing is additive with the effect of lag whether the cue is informative or non-informative. This pattern of results lends strong support to the hypothesis that spatial selection and identity extraction are separable functions in visual search.

General Discussion

The principal objective of the present work was to examine the separability of spatial-selection and identity-extraction processes in visual search by varying the two factors independently. This was done by combining two paradigms: spatial cueing and the AB within the same experiment. Spatial selection was manipulated by the presence or absence of a spatial cue directly before the second target. Identity extraction was manipulated by varying the temporal lag between the first and the second target.

In Experiment 2.1 the spatial cue was informative and the dependent measure was accuracy of second-target identification. Performance in the Cue condition was substantially higher than in the No-Cue condition. Importantly, the difference between cued and uncued performance was invariant across all three inter-target lags. Based on additive-factors logic, this additivity was taken as evidence that spatial selection and identity extraction are separable factors in visual search. A possible limitation of Experiment 2.1 arose from the finding that performance in the No-Cue condition was near a floor level imposed by the response scale. This was avoided in Experiment 2.2 by changing the dependent measure: instead of accuracy, we used a dynamic threshold-tracking procedure to find the critical exposure duration at which the second target could be identified on approximately 80% of the trials. The results were comparable to those of Experiment 2.1, and buttressed the conclusion of separability. In Experiment 2.3, the informative spatial cue used in Experiments 2.1 and 2.2 was replaced by a non-informative cue. The results again supported the hypothesis that spatial selection and identity extraction are separable processes in visual search.

Comparisons with related studies

Several recent studies have investigated the relationship between spatial cueing and the AB, although none of them was concerned explicitly with the separability of spatial and identity processes. Olivers (2004) investigated the effect of the AB on spatial processing in a study that, while addressing some of the issues tackled in the present work, differed from it in several ways. There were up to six simultaneous spatial cues, the SOA between the cue and the second target was considerably longer than in the present experiments (800 vs. 90 ms), and a pattern mask was presented directly after the cue display. The results showed that spatial processing was impaired during the AB but only when the number of cues was greater than one. In contrast, consistent with the present results, the interaction effect between cueing (cue present/absent) and the AB (inter-target lag short/long) was not significant when the display contained only one cue¹. Thus, Oliver's conclusion of interdependence between spatial processing and the AB seems to apply only in the case of multiple cues. It is possible that the procedural differences between the two studies activated different mechanisms (e.g., spatial orienting vs. spatial memory) with consequent differences in the ways the search task was performed.

A study that perhaps comes closest to the present work has been reported by Nieuwenstein, Chun, van der Lubbe, & Hooge (2005, Experiment 4). In that experiment, a spatial cue was presented at the location of the second target 94 ms before target onset. Consistent with the present findings, the cue was effective during the period of the AB. But instead of being parallel as in the present study (e.g., Figures 2.3 and 2.4), the functions for the Cue and No-Cue conditions converged at the longer lag. The

discrepancy between the two studies, however, has been ascribed to a procedural artefact in the Nieuwenstein et al. study. Recent work in our laboratory has shown that the convergence of the two functions in Nieuwenstein et al.'s Experiment 4 arose from a data-limitation ceiling which prevented second-target accuracy from exceeding 70%, regardless of cueing. When the ceiling limitation was removed, the interaction disappeared, and the two functions became parallel, much as the functions obtained in all the present experiments (Ghorashi, Enns, Spalek, & Di Lollo, in press).

One other study is of relevance to the present work, even though it did not employ spatial cues. Jiang and Chun (2001) employed flanker interference in an AB paradigm to examine the effects of spatial factors on second-target identification at short *versus* long inter-target lags. The results showed evidence of interdependence between spatial and identity processing. Namely, the perceptual interference caused by the flankers was more pronounced in the short-lag condition. On the face of it, this outcome contrasts with the present finding of separability. Jiang and Chun's results, however, could have been affected by much the same ceiling constraints as the study by Nieuwenstein et al. (2005). Namely, performance at the long inter-target lag was obviously compressed against a ceiling, causing the functions to converge thus producing an appearance of interdependence. The source of the performance ceiling differed in the two studies: data limitation (Nieuwenstein et al.) or upper limit of the response scale (Jiang & Chun). The consequence, however, was the same in that the ceiling constraint could have prevented parallel functions – and hence separability – from being in evidence.

A theoretical account

An account of the separability of spatial and identity processes demonstrated in the present work can be given on the basis of the neuroanatomical and neurophysiological evidence for two separate visual pathways: dorsal and ventral. The dorsal pathway is driven mainly by the magnocellular (M) neurons, whereas the ventral pathway is driven principally by the parvocellular (P) neurons (Vidyasagar, 1999). These two types of neurons carry different information. The M neurons, characterized by relatively large receptive fields and fast conduction velocities, are insensitive to colour but respond readily to movement and low-contrast stimuli. The P neurons are characterized by smaller receptive fields, are sensitive to colour, and have slower conduction velocities.

These different response characteristics make the dorsal and ventral pathways suitable for processing different types of visual information. The idea of functional specialization was first realized by Ungerleider and Mishkin (1982) who referred to the two pathways as “Where” and “What” because space-related processes such as motion and depth perception were shown to be carried out along the dorsal stream, whereas object identification was shown to engage mainly the ventral stream. A similar distinction has been made by Milner and Goodale (1995) who preferred the term “How” to “Where”.

We suggest that the separability of the mechanisms underlying spatial selection and identity extraction demonstrated in the present experiments can be mapped directly on the functional distinction between dorsal and ventral streams. Specifically, we suggest that the exogenous spatial cues used in the present experiments were processed mainly along the dorsal pathway, and that the identification of the two letter targets was carried out

principally along the ventral pathway. Within this conceptual framework, spatial selection and identity extraction are separable because they are mediated by mechanisms that are anatomically and functionally separable.

The functional distinction between the two pathways is also supported by clinical evidence from patients with either exclusive ventral-stream damage, which leaves them with visual agnosia (Milner et al., 1991), or exclusive dorsal-stream damage which makes them unable to reach for objects that they can describe verbally. The latter condition is called optic ataxia, and is often associated with Bálint's syndrome (Bálint, 1909). Behavioural studies with neurologically intact subjects have also provided hints that spatial selection and identity extraction may be separable functions performed along the dorsal and ventral pathway. For example, Liu, Chua, and Enns (2008) have shown that while the process of identifying an object (a ventral-stream task) interferes with the process of planning to reach a second object (another ventral-stream task), it does not interfere with the visually guided control necessary for completing the action (a dorsal-stream task). Also, Nieuwenhuis, Jepma, La Fors, & Olivers (2008) conducted three attentional blink experiments in which they varied the background colour, luminance, and the degree of adapting flicker, manipulations all designed to influence the degree of magnocellular involvement in perception. They found no influence of any of these factors on the second target deficit, consistent with the notion that the standard single-stream attentional blink task does not have a strong magnocellular contribution. Finally, the separability of localization and identification processes is confirmed by evidence that a target can be localized without necessarily being identified, both in a visual search task (Atkinson & Braddick, 1989) and in an attentional blink task (Ghorashi et al., 2008).

Finally, the separability of localization and identification processes is confirmed by evidence that a target can be localized without necessarily being identified (Atkinson & Braddick, 1989; Ghorashi et al., 2008).

Concluding comments

Two further issues need to be raised regarding the separability of location and identity processes. First, earlier work has shown that visual search is postponed during the AB (Ghorashi, Smilek, & Di Lollo, 2007). In light of the present result that spatial cueing is unimpaired during the AB, it is plausible to assume that what is postponed during the AB is the process of second-target identification.

Second, the cueing processes involved in the present experiments were invariably stimulus-driven, engaging principally the dorsal pathway. Within the conceptual framework outlined above, it should be expected that, were the cue to require processing along the ventral pathway, separability would no longer be in evidence. This is because both the cue and the targets would require access to the same processing mechanisms. Evidence consistent with this expectation has been reported by Dell'Acqua, Sessa, Jolicœur, & Robitaille (2006). In that study, the first target was a pair of digits to be identified (a ventral-stream task), and the second-target task involved spatial selection based on colour (also a ventral-stream task). Consistent with the present theoretical conviction, the results showed that spatial selection was impaired during the AB. Whether corresponding results are obtained in a cueing experiment in which the cue and the target are processed along the same pathway remains to be established.

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CHAPTER 3:

Spatial Cueing Does Not Affect the Magnitude of the Attentional Blink³

Attentional limitations in visual processing are revealed by a phenomenon known as the *attentional blink* (AB): identification of the second of two targets (T2) is impaired when presented less than about 500 ms after the first target (T1; Raymond, Shapiro, & Arnell, 1992). The deficit is commonly found to be most pronounced when the inter-target lag is short, and to diminish progressively as the lag is increased.

Several factors are known to influence the magnitude of the AB. For example, the deficit is much reduced when T2 is one's own name (Shapiro, Caldwell, & Sorensen, 1997) or when the observer adopts a more relaxed approach to the task (Olivers & Nieuwenhuis, 2005). Whether cueing also affects the magnitude of the AB has been investigated by Nieuwenstein, Chun, van der Lubbe, and Hooge (2005). They set out to find out whether the magnitude of the AB is reduced when T2 is preceded by a cue that shares the target's defining characteristic or, equivalently, by a cue that indicates the location of an upcoming target.

Based on the results of four experiments, Nieuwenstein et al. (2005) concluded that cueing of T2 reduces the magnitude of the AB. That conclusion is questioned in the present work. We argue that Nieuwenstein et al.'s results were vitiated by a performance ceiling imposed by data limitation. The problem is perhaps best exemplified in Nieuwenstein et al.'s (2005) Experiment 4.

³ A version of this chapter has been accepted for publication. Ghorashi, S., Enns, J. T., Spalek, T. M., & Di Lollo, V. (2009). Spatial cueing does not affect the magnitude of the attentional blink. *Attention, Perception, & Psychophysics*.

In that experiment, the basic display consisted of four square outlines that acted as place holders for the stimuli: above, below, left, or right of a central fixation cross. The display sequence began with T1 (a letter) displayed briefly inside a randomly-chosen placeholder, immediately followed by a mask. T2, also followed by a mask, was presented inside one of the three remaining placeholders, at random, after an inter-target lag that was either short (306 ms) or long (706 ms). Importantly, a spatial cue (a + sign) was presented in the T2-placeholder 94 ms before the onset of T2.

Each observer served in a preliminary experiment aimed at keeping performance well below the 100% ceiling imposed by the response scale. In that experiment, a single target was followed by a mask. The relative exposure duration of the target and the mask was varied systematically within a total duration of 106 ms. As the duration of the target was increased, the duration of the mask was decreased correspondingly. The specific combination of target and mask that yielded 70% correct target identifications, separately for each observer, was used in the experiment proper as the duration of T1 plus mask and T2 plus mask.

The results of Nieuwenstein et al.'s (2005) Experiment 4 are illustrated in Figure 3.2b. Cueing is seen to enhance accuracy of T2 identification at the short lag but not at the long lag. This result led to the conclusion that cueing reduces the magnitude of the AB.

On the face of it, the finding that cueing did not facilitate T2 identification at the longer lag (Figure 3.2b) seems contrary to the well-established finding that cueing the location at which a target is about to appear leads to substantial benefits (e.g., Colegate, Hoffman, & Eriksen, 1973). By the same token, the finding that cueing enhanced T2

identification only at the shorter lag appears odd. Namely, a cue that is demonstrably ineffectual outside the period of the AB (lag = 706 ms) appears to become effectual within the period of the AB (lag = 306), just when stimulus processing is supposed to be most impaired.

Here, we claim that both these problems are likely to have arisen from a procedural artifact. Namely, while avoiding the 100% ceiling imposed by the response scale, the preliminary procedure implemented by Nieuwenstein et al. (2005) might have introduced a ceiling imposed by data limitation. The principal aim of the preliminary procedure was to impoverish a single target so that it could not be identified correctly more than 70% of the times. It is, therefore, not surprising that, in the experiment proper, T2 performance could not exceed that 70% level (Figure 3.2b). It is likely that the impoverishment was mediated by temporal-integration masking in which the target and the mask are perceived as a single compound stimulus. This degradation resulted in an effective data limitation that constrained performance to 70% not only for T2 (Figure 3.2b) but also for T1 which was identified correctly on 69% of the trials.

As did the experiment of Nieuwenstein et al. (2005, Experiment 4), the present experiment aimed at investigating the effect of a spatial cue on the magnitude of the AB. The present procedures, however, avoided a performance ceiling by employing a dynamic threshold-tracking procedure known as PEST (Parameter Estimation through Sequential Testing; Taylor & Creelman, 1967). The display sequence was the same as in the study of Nieuwenstein et al., except that T2 was displayed for only 13.3 ms and was separated from the trailing mask by an inter-stimulus interval (ISI) during which the screen was blank. An ISI was inserted between the target and the mask in order to

minimize the probability of temporal integration (Di Lollo, Hogben, & Dixon, 1994). The duration of the ISI was varied dynamically by PEST, separately for each observer, to converge on a level of 70% correct T2 responses. The dependent measure was the critical ISI (ISI_c) at which the observer obtained 70% correct responses. By its very nature, ISI_c is free from ceiling constraints.

Method

Observers

Twenty-one undergraduate volunteers at Simon Fraser University participated for class credit or payment. All reported normal or corrected-to-normal vision and were naïve to the purpose of the experiment.

Apparatus and stimuli

The stimuli consisted of sequences of two upper-case letters chosen randomly without replacement on each trial from the English alphabet, excepting I, O, Q, and Z. All stimuli were black, subtended approximately 1° of visual angle, and were presented on a mid-grey background (approximately 42 cd/m^2) at a luminance of approximately 0.5 cd/m^2 as measured by a Minolta LS 100 luminance meter. The screen's refresh rate was 75 Hz. Observers sat in a dimly-lit room, and viewed the displays from a distance of approximately 60 cm.

Procedure

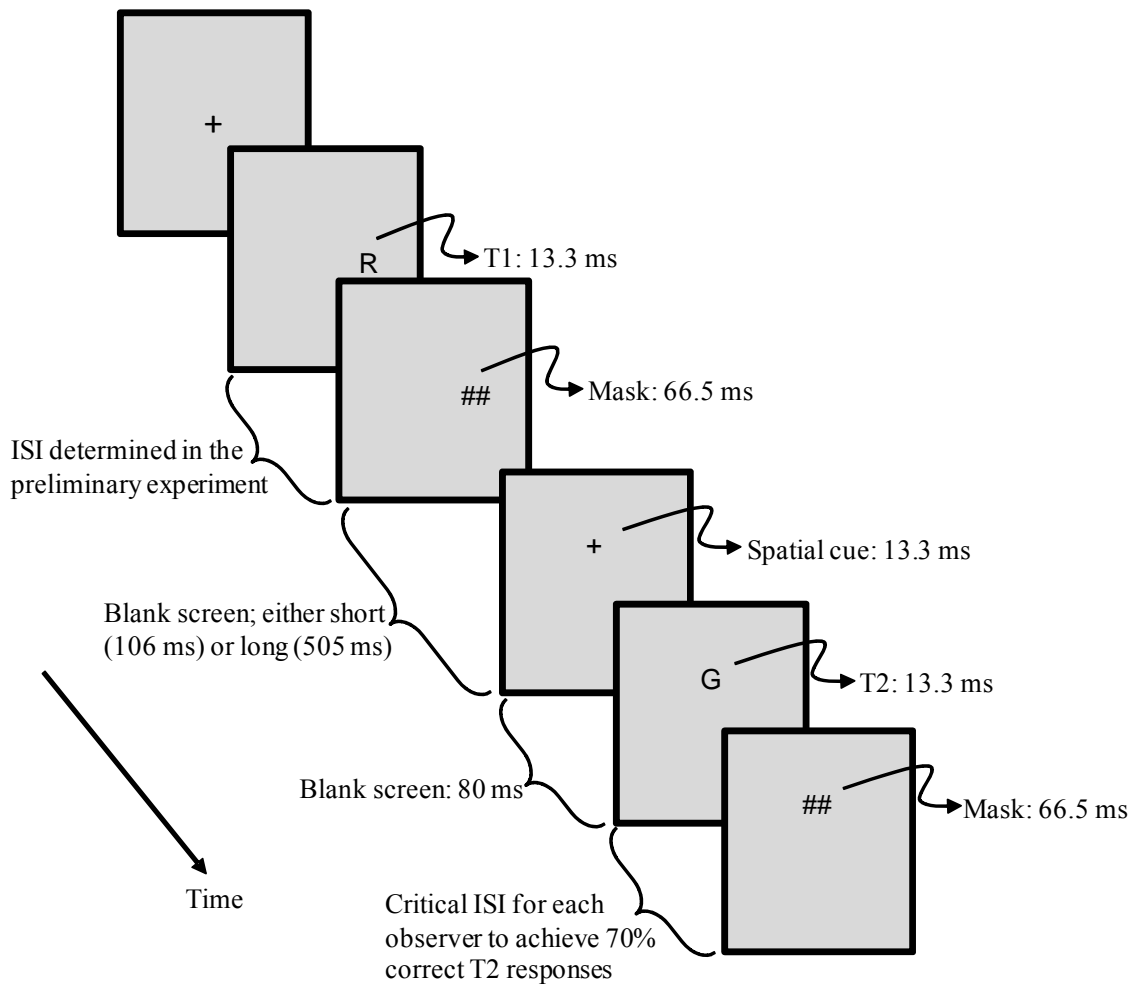
An overriding design consideration was to replicate as closely as possible the procedures in Nieuwenstein et al.'s (2005) Experiment 4. The sequence of stimuli was as follows (see Figure 3.1). After the observer initiated a trial by pressing the spacebar, the

fixation cross disappeared from the centre of the screen and T1 was presented for 13.3 ms in one of four screen locations, chosen randomly on each trial: 2° (centre-to-centre) above, below, to the left or to the right of the fixation cross. T1 was followed by a blank ISI which was followed by a mask consisting of two side-by-side # signs displayed for 66.5 ms. The ISI between T1 and its mask was fixed throughout the experiment, and was determined separately for each observer in a preliminary procedure in which PEST was used to find the ISI at which the observer could identify a single target followed by the ## mask approximately 70% of the times. The mean ISI, averaged across observers, was 38.7 ms (standard deviation = 16.3). Thus, on average, the exposure duration for T1, the ISI, and the mask was 118.5 ms.

The T1-mask was followed by a blank screen displayed for 106 ms on half of the trials and for 505 ms on the other half. On half of the trials in each of the two conditions, the blank screen was followed by a plus sign that served as a spatial cue for T2 because it appeared in the same location as the upcoming T2. The cue was displayed for 13.3 ms, followed by a blank screen for 80 ms. On trials in which the spatial cue was not displayed, the duration of the blank screen was increased to 93.3 ms. T2 was presented for 13.3 ms in one of the remaining three screen locations (other than the T1 location), chosen randomly on each trial. T2 was followed by a blank ISI, which was followed by the ## mask for 66.5 ms. Thus, the two targets were separated either by a short SOA (lag was approximately 318 ms) or by a long SOA (approximately 717 ms).

Figure 3.1. Sequence of events on each trial. On this trial, T2 (second target) was cued.

T1 = first target; ISI = inter-stimulus interval; ms = milliseconds.



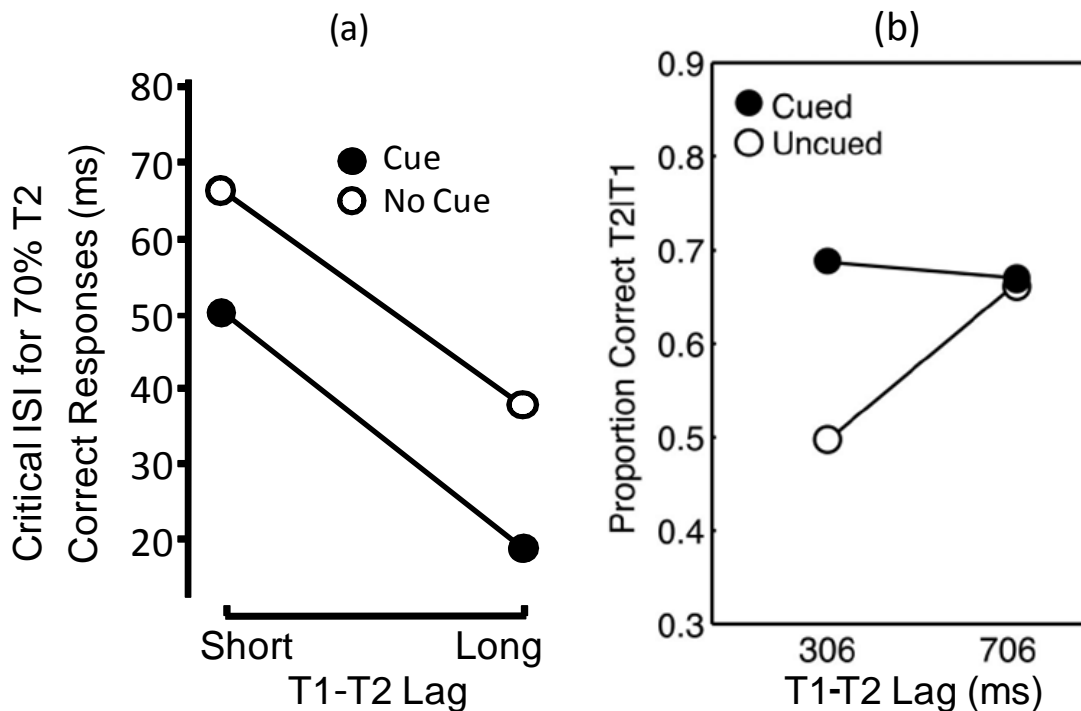
The principal dependent variable in the present experiment was the duration of the critical ISI (ISI_c) between T2 and its mask at which any given observer could identify T2 approximately 70% of the times. The ISI between T2 and its mask was varied

dynamically by PEST which reduced the ISI when the observer's response accuracy exceeded the criterial level, and increased it when accuracy was too low. A Wald (1947) sequential likelihood-ratio test determined whether the immediately preceding run of responses yielded an event proportion greater or less than 70%. The Wald routine was called only on trials in which T1 had been identified correctly. The PEST end-run consisted of 16 trials after three reversals in the direction of adjustment of the ISI had been recorded. The final score (ISI_c) was the mean ISI over those last 16 trials. Thus, ISI_c represents the duration of the mask-free interval after T2 offset necessary to achieve the criterial level of accuracy, separately for each observer. The observers were required to report both targets in any order, guessing if unsure. Thus, the design was a 2 (T1-T2 lag: short or long) x 2 (Cue: present or absent) factorial.

Results and Discussion

The mean percentages of correct responses for T1, averaged over lags, were 59.7% and 57.9% for the Cue and No-cue conditions, respectively. A 2 (Lag: short or long) x 2 (Cueing: Cue or No-Cue) repeated-measure analysis of variance (ANOVA) performed on the T1 scores revealed no significant effects of Lag or Cueing (both $F_s < 1$), and no significant interaction effect, $F(1, 20) = 1.41, p = .25$. The ISI_c s were averaged across observers, separately for each lag and cueing condition, and are illustrated in Figure 3.2a. The scores were analyzed in a 2 (Lag: short or long) x 2 (Cueing: Cue or No-Cue) repeated-measure ANOVA. The analysis revealed significant effects of Lag, $F(1, 20) = 19.22, p < .001$, and Cueing, $F(1, 20) = 6.19, p = .02$. The interaction effect was not significant, $F < 1$.

Figure 3.2. (a) Results of the present experiment. T1-T2 lag varied slightly across observers, depending on the duration of the ISI between T1 and the trailing mask, as determined in the preliminary procedure. Averaged across observers, the Short Lag was 318 ms, and the Long Lag was 717 ms. (b) Results of Experiment 4 of Nieuwenstein et al. (2005). T1 = first target; T2 = second target; ISI = inter-stimulus interval; ms = milliseconds.



While avoiding ceiling effects, the PEST procedure is open to possible floor effects that might prevent an interaction from being in evidence. A floor effect could occur if the ISI between T2 and its mask was decreased to the irreducible minimum of zero refresh frames (i.e., $ISI_c = 0$). An ISI_c equal to zero was obtained by two observers at the long inter-target lag in the Cue condition, and by two observers in the long inter-target lag in the No-Cue condition. The outcome of an ANOVA performed on the data

that did not include those observers was virtually identical with the earlier analysis. The analysis revealed significant effects of Lag, $F(1, 16) = 10.81, p < .005$, and Cueing, $F(1, 16) = 13.67, p = .002$. The interaction effect was again not significant, $F < 1$. Thus, possible floor effects were not a consideration in the present experiment.

Spatial cueing enhanced T2 performance, but it did so equally across lags (Figure 3.2a). Namely, the cue enhanced T2 performance to the same extent whether T2 was presented during the period of the AB or beyond it. This means that spatial cueing and the AB were independent effects. The present findings strongly suggest that Nieuwenstein et al.'s (2005, Experiment 4) conclusion that cueing reduces the magnitude of the AB was based on an artefact brought about by a ceiling imposed by data-limitation. When the ceiling is removed, as was done in the present work, the results show that spatial cueing does not affect – and is not affected by – the AB.

It must be noted that Nieuwenstein et al. (2005) were not unaware of a data limitation in their experiments: "... cueing did not enhance report ... when performance was data limited in a dual-target condition" (p. 1470). What they did not consider was that it might have been impossible for T2 performance to exceed the ceiling imposed by the data limitation, whether or not T2 was precued, or whether it was presented during the period of the AB or beyond it. The finding that a leading cue did not facilitate the report of a trailing target outside the period of the AB is itself remarkable because it is at odds with the established finding in the spatial cueing literature. That finding ceases to be anomalous, however, when seen as the end result of a ceiling imposed by data limitation.

Nieuwenstein et al.'s (2005) results led to two major conclusions. First that "...the AB can be markedly reduced or even fully prevented when T2 is precued" (p. 1473). This conclusion is disconfirmed by the present results (Figure 3.2a) which point instead to a performance ceiling as the critical factor. Second that, in agreement with predictions from the Delayed Attentional Engagement (DAE) hypothesis (Nieuwenstein et al., 2005), "... cueing appears to counteract a delay in the selection of potential targets for consolidation" (p. 1473). In a restricted sense, this conclusion is valid and consistent with the outcomes of the present work and with the conventional finding that cueing facilitates target processing. However, the present finding that the extent of cueing-linked facilitation is invariant with inter-target lag cannot be explained by the DAE hypothesis in which cueing is said to be effective only during the period of the AB.

There are several potential accounts for the independence of cueing and the AB seen in the present work. One plausible option is that cue localization and target identification might take place along distinct processing pathways. Spalek, Falcon, and Di Lollo (2006) have proposed a hybrid input-filtering model in which different classes of stimuli are processed along separate pathways. Salient stimuli, such as the spatial cue employed in the present study, are said to gain direct access to high-level processing along a dedicated pathway that is free from the AB bottleneck.

A dual-pathway account has also been proposed by Ghorashi, Enns, and Di Lollo (2008), in terms of the distinction between dorsal and ventral visual pathways (Ungerleider & Mishkin, 1982). They have proposed that the independence of spatial-selection and identity-extraction processes can be mapped directly on the functional distinction between dorsal and ventral streams. Specifically, they have suggested that

spatial selection is carried out mainly along the dorsal pathway, and that target identification is carried out principally along the ventral pathway. Within this conceptual framework, cueing was not affected by the AB in the present work because spatial selection and identity extraction are mediated by processing mechanisms that are anatomically and functionally distinct.

Whether non-spatial cueing is also independent of the AB remains to be determined. A suggestion of independence is provided by the outcome of Nieuwenstein et al.'s (2005) Experiment 2. In that experiment, all stimuli were presented in rapid serial visual presentation in the centre of the screen. The distractors were black letters and the targets were coloured digits. In the cueing conditions, T2 was reliably preceded by a cue in the form of two distractors of either the same or different colour from T2. In a No-Cue condition, T2 was preceded by black distractors. The finding of principal interest for the present purpose was that the functions for the Different-Colour Cue and the No-Cue conditions, while differing from one another in level, were parallel much as the functions seen in Figure 3.2a. This suggests that cueing may not affect the magnitude of the AB even when the cueing is non-spatial. Further experimentation is clearly required, however, in order to reach an unambiguous conclusion.

One last issue needs to be raised. In the present work, the abrupt onset of the spatial cue caused attention to be driven exogenously. Under these conditions, cueing was not impaired during the AB. Whether cueing would remain unimpaired under conditions in which attention is driven endogenously is uncertain. On one hand, Dell'Acqua, Sessa, Jolicoeur, & Robitaille (2006) have reported that the endogenous control of attention is impaired during the AB. On the other hand, Zhang, Shao,

Nieuwenstein, & Zhou (2008) have found that endogenous control is not impaired during the AB. A resolution of this issue, however, is beyond the scope of the present study.

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CHAPTER 4:

Are Spatial Selection and Identity Extraction Separable When Attention is Controlled Endogenously?⁴

A visual target presented in a field of distractors is identified more quickly and more accurately when its location is singled out by a temporally leading spatial cue (Colegate, Hoffman, & Eriksen, 1973; Eriksen & Hoffman, 1972). It is commonly agreed that a spatial cue acts to orient attention to a specific location in the visual field, and that attention then enhances target identification (e.g., Wolfe, 2006; Wolfe, Cave, & Franzel, 1989). Whether the mechanisms underlying the processes of spatial selection and identity extraction function independently or interact with one another has been investigated by Ghorashi, Di Lollo, and Klein (2007) and by Ghorashi, Enns, Klein, and Di Lollo (2009) who found the two factors to be separable. The present experiments examined whether this separability occurs also when the processes involved in attentional orienting are goal-directed rather than stimulus-driven, as was the case in the earlier studies.

Ghorashi et al. (2009) combined two experimental paradigms to influence spatial selection and identity extraction separately within the same experiment. Spatial selection was manipulated by the presence or absence of a spatial cue displayed directly before the target in a visual-search array. Identity extraction was manipulated by means of the phenomenon known as the *attentional blink* (AB) which is an impairment in the identification accuracy of the second of two targets inserted in a stream of distractors

⁴ A version of this chapter has been accepted for publication. Ghorashi, S., Spalek, T. M., Enns, J. T., & Di Lollo, V. (2009). Are spatial selection and identity extraction separable when attention is controlled endogenously? *Attention, Perception, & Psychophysics*.

displayed in rapid serial visual presentation (RSVP). This second-target deficit is obtained when the temporal lag between the two targets is less than about 500 ms (Raymond, Shapiro, & Arnell, 1992). Thus, identity extraction is impaired when the lag is short but not when it is long.

Additive-factors logic (Sternberg, 1969) was employed by Ghorashi et al. (2009) to examine the separability of spatial selection, as manipulated by spatial cueing, and identity extraction, as manipulated by the AB. They reasoned that if cueing and the AB exhibited an orthogonal (additive) relationship, the hypothesis would be supported that the underlying mechanisms were separable. If, on the other hand, cueing and the AB exhibited an interactive (multiplicative) relationship, the alternative hypothesis of interdependence would be supported, suggesting that spatial selection and identity extraction shared common mechanisms. The results showed that the beneficial effect of the cue was the same when inter-target lag was short as when it was long. This means that the AB did not interfere with the processing of the spatial cue and, therefore, that the two processes were independent of one another.

Ghorashi et al. (2009) accounted for these findings by relating them to two major parallel pathways in primate vision: the dorsal and the ventral pathways. As well as being anatomically distinct, the two pathways are known to carry and process different types of information. Neurons in the dorsal stream are insensitive to colour but respond readily to movement and low-contrast stimuli, attributes that make them suitable for processing spatial information. In contrast, neurons in the ventral stream are sensitive to colour, have smaller receptive fields and slower conduction velocities, attributes that make them more suitable for processing the identity of objects. This functional

specialization was first realized by Ungerleider and Mishkin (1982) who referred to the dorsal and the ventral pathways as the “Where” and the “What” pathways, respectively.

According to Ghorashi et al. (2009), the separability of spatial selection and identity extraction can be mapped directly on the functional distinction between dorsal and ventral streams. Specifically, they suggested that spatial selection is carried out mainly along the dorsal pathway, and that target identification is carried out principally along the ventral pathway. Within this conceptual framework, spatial selection and identity extraction are separable because they are mediated by mechanisms that are anatomically and functionally distinct.

This dual-pathway approach provided a good account of the separability of location and identity processes because it was plausible to suppose that the cue (a briefly-presented dot at the location of the upcoming target) and the target (a letter to be identified and discriminated from other letters) were processed along separate pathways. Inherent in this account is the prediction that the separation of location and identity processing would no longer be in evidence if the spatial cue required processing mechanisms that were also required for the processing of the target. This would be the case in an experiment in which the spatial cue itself required identification, thus engaging the same ventral-stream mechanisms required for identification of the target. The present work was designed to test this prediction.

Experiment 4.1

Experiment 4.1 built on the experiments reported by Ghorashi et al. (2007) and by Ghorashi et al. (2009). As in those experiments, spatial selection was manipulated by the presence or absence of a spatial cue, and identity extraction was manipulated by

presenting the second target either within the period of the AB, at short inter-target lags, or beyond it. The major difference was that in the present experiment the spatial cue itself required identification.

The display consisted of an RSVP stream of distractors (black letters) containing two targets. The first target was a white letter to be identified; the second target was a "T", tilted left or right, inserted in a circular search array of 11 rotated "L"s, arranged as in a clock face. The spatial cue was a red number between 01 and 12 presented just above the central RSVP stream, shortly before the second target. The observers were told that the second target would be located at the clock location indicated by the number cue.

Given that this task required identification of both the cue and first target, it is plausible to assume that the two stimuli engaged processing mechanisms that were at least partly overlapping. In terms of the dual-pathway framework outlined above, this means that both stimuli engaged ventral-pathway mechanisms. Using additive-factors logic, we would expect that stimuli that share common underlying mechanisms would exhibit an interactive – rather than additive – relationship. In practice, we would expect the effectiveness of the number cue to be impaired at short inter-target lags, when it must share processing mechanisms with the first target but not at longer lags. Thus, instead of the independence reported by Ghorashi et al. (2009), we would expect spatial cueing and the AB to exhibit an interactive relationship.

Method

Observers

Twenty-nine undergraduate students at Simon Fraser University participated for course credit. All reported normal or corrected-to-normal vision.

Apparatus and Stimuli

Stimuli were displayed on an NEC AccuSync 70 colour monitor, refreshed at 75 Hz, controlled by an IBM-compatible microcomputer. The background was mid-grey and contained a black fixation cross that subtended 0.5° of visual angle at the centre of the screen. The stimuli in the central RSVP stream consisted of black upper-case letters (distractors) and a white upper-case letter (the first target), all subtending 0.6° of visual angle vertically. The search array containing the second target consisted of 11 randomly-rotated "L"s and one tilted "T" (the target). The letters in the search array subtended 0.5° of visual angle vertically. The "T" was tilted 45° either to the left or to the right. The stimuli in the search array were spaced regularly around an imaginary clock face of 2.5° radius, centered at fixation. The spatial cue was a red two-digit number between 01 and 12, subtending 0.5° vertically, chosen randomly on each trial. The number cue was presented in the same frame as the distractor item preceding the second target in the RSVP stream, and was positioned directly above the distractor item (1° centre-to-centre).

Procedure

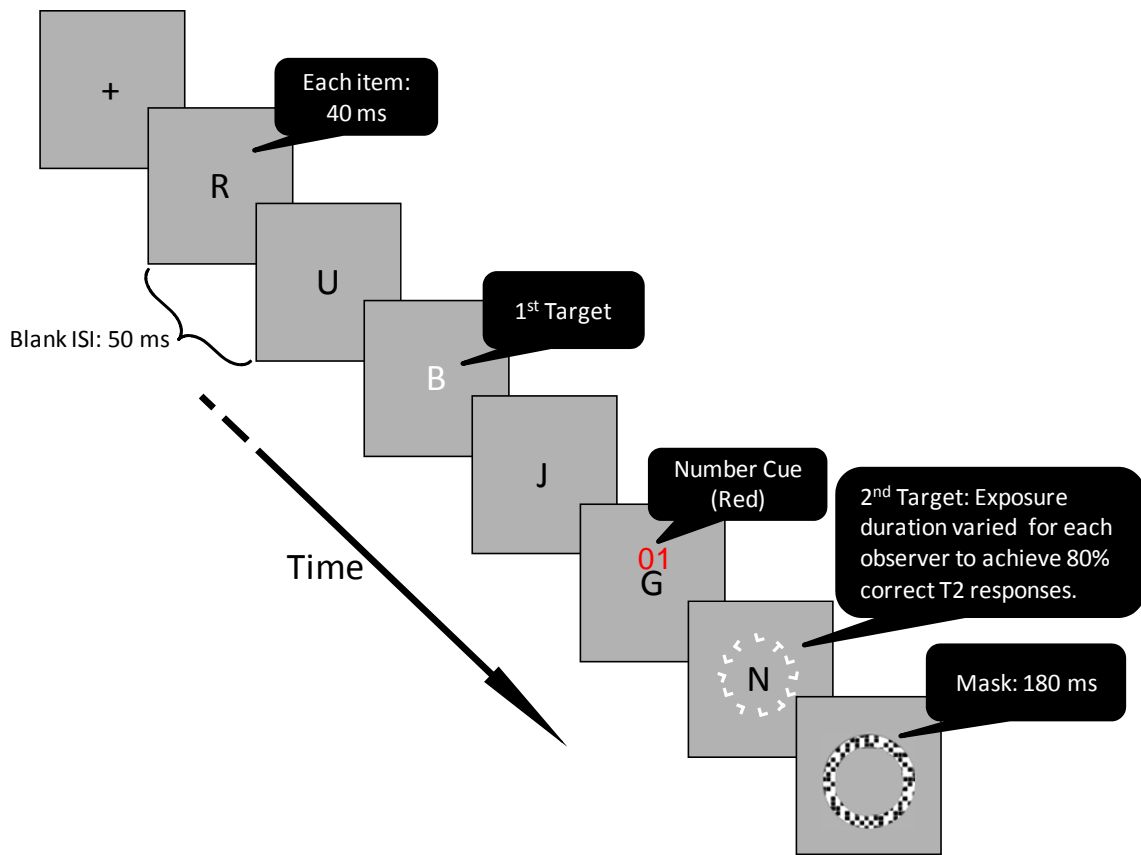
All displays were viewed from a distance of approximately 60 cm. At the beginning of each trial the fixation cross was presented in the centre of the screen. Observers initiated each trial by pressing the spacebar, at which point the fixation cross disappeared and the RSVP sequence began after a random delay of 400-800 ms. The distractors (black letters) in the RSVP stream were drawn randomly without replacement from the English alphabet excepting Q. Each letter was displayed for 40 ms and was separated from the next letter by an inter-stimulus interval (ISI) of 50 ms, during which the screen was blank. This resulted in a stimulus-onset asynchrony (SOA) of 90 ms

between successive items. The first target was preceded in the RSVP stream by between 5 and 10 distractors, at random.

The search array containing the second target was presented at one of three inter-target lags: Lag 1 (in the frame directly following the first target), Lag 3 (in the third frame after the first target), or Lag 7 (in the seventh frame following the first target). At Lags 3 and 7, distractors continued to be presented throughout the inter-target lag. There were two blocks of trials: in the Cue block, a spatial cue – a red number between 01 and 12 presented just above the central RSVP stream – was presented for 40 ms in the RSVP frame preceding the search array. Thus the SOA between the cue and the target was 90 ms. The observers were told that the second target would be located at the clock location indicated by the number cue. The No-Cue block was the same as the Cue block except that the cue was not presented. The observers were instructed to take advantage of the spatial information provided by the cue. In brief, the design of Experiment 4.1 was a 2 (Cue: present or absent) x 3 (Lags: 1, 3, 7) within-subject factorial.

The circular search was followed immediately by a 180-ms doughnut-shape mask that completely covered the search array. The pixels inside the mask were randomly coloured black or white. The RSVP stream of distractors continued while the search array was displayed. Examples of the stimuli and the sequence of events on any given trial are illustrated in Figure 4.1. At the end of each trial, observers identified the first target by pressing the corresponding key on the keyboard, and then indicated whether the second target was tilted to the left or to the right by pressing the left or the right shift key.

Figure 4.1. Sequence of events on each trial. On this trial, the second target was cued.



The dependent measure in this experiment was the critical exposure duration (DUR_c) for which the second target needed to be displayed in order to achieve 80% accuracy. The exposure duration of the circular search array containing the second target was varied dynamically by a threshold-tracking staircase procedure called Parameter Estimation by Sequential Testing (PEST; Taylor & Creelman, 1967). PEST reduced the exposure duration when the observer's response accuracy exceeded the critical level, and increased it when accuracy was too low. A Wald (1947) sequential likelihood-ratio test determined whether the immediately preceding run of responses yielded an event

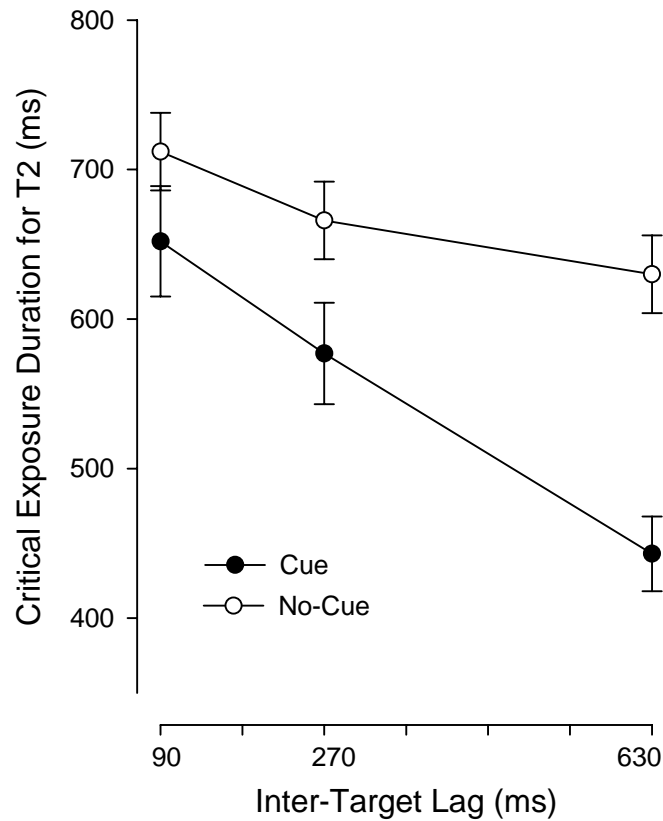
proportion greater or less than 80%. The Wald routine was called only on trials in which the first target had been identified correctly. The PEST end-run consisted of 16 trials after three reversals in the direction of adjustment of exposure duration had been recorded. The final score (DUR_c) was the mean exposure duration of the search array over the last 16 trials. Thus, DUR_c represents the duration of the mask-free interval necessary to achieve the criterial level of second-target accuracy, separately for each observer. This procedure was adopted in order to avoid the 100% ceiling constraints imposed by the response scale when identification accuracy is used as the dependent measure.

Results and Discussion

The mean percentages of correct responses for the first target, averaged over lags, were 88.5% and 95.2% for the Cue and No-cue conditions, respectively. The mean DUR_c values for the second target at each lag are illustrated in Figure 4.2. An analysis of variance (ANOVA) performed on the data in Figure 4.2 comprised two within-subjects factors: Cue (present, absent) and Lag (1, 3, 7). The analysis revealed significant effects of Cue, $F(1, 28) = 26.36, p < .001$, and Lag, $F(2, 56) = 16.78, p < .001$. The interaction effect was also significant, $F(2, 56) = 4.54, p = .015$.

Figure 4.2. Results of Experiment 4.1. Bars represent the standard errors of the mean.

T2: Second Target; ms: milliseconds.



While avoiding ceiling effects, the PEST procedure is open to possible floor effects. A floor effect could occur if the exposure duration of the second target was decreased to the irreducible minimum of one refresh frame (13.3 ms). This was never the case in the present experiment in which the lowest individual DUR_c recorded in any of the six conditions was 190 ms.

As seen in Figure 4.2, much shorter exposure durations were required when the location of the second target was cued. Also, a significant AB deficit was in evidence, with the values of DUR_c decreasing as Lag was increased. The important consideration

for the objective of the present work, however, is that the advantage conferred by the spatial cue was significantly smaller when the inter-target lag was short than when it was long. On the tenets of additive-factors logic, this suggests that the number-cue and the letter-target engaged common processing mechanisms.

This pattern of results is consistent with predictions from the dual-pathway framework outlined above. Given that both the number-cue and the letter-target required identification, it is plausible to assume that the two stimuli engaged common processing mechanisms within the ventral stream. Identification of the cue was then impaired at the shorter lags, when the necessary processing mechanisms were engaged in identifying the first target. The resulting delay in processing the identity of the cue caused a corresponding delay in the deployment of focal attention to the location of second target. A longer DUR_c was then required in order to escape the trailing mask.

In contrast, no such impairment in the processing of the spatial cue was in evidence in the experiments of Ghorashi et al. (2009). This is because the cue (a dot demarcating the location of the second target) did not need to be identified. Without the need for identification, the cue did not engage the same mechanisms as the first target (a letter to be identified) and was, therefore, processed along a different (dorsal) pathway.

A further issue arises regarding the impairment of cueing during the AB in the present experiment. Utilizing the information provided by the cue involved at least two sequential steps. The first was to identify the number-cue; the second was to re-direct focal attention to the clock-location indicated by the cue. Thus, the reduced effectiveness of the cue during the AB (Figure 4.2) could have arisen at either or both of these steps. Experiment 4.2 was designed to determine the source of interference. This was done by

eliminating the first step (cue identification) while maintaining the second step (redirection of focal attention).

Experiment 4.2

In Experiment 4.2 the number-cue used in Experiment 4.1 was replaced by a small dot presented at the clock-location opposite the location of the target in the search array. This eliminated the requirement to identify the cue but maintained the requirement to redirect focal attention to the target's location.

Method

Observers

Twenty-two undergraduate students at Simon Fraser University participated for course credit. None had participated in Experiment 4.1, and all reported normal or corrected-to-normal vision.

Apparatus, Stimuli, and Procedure

These were the same as in Experiment 4.1 except for the spatial cue. Instead of the number-cue, the cue consisted of a small white dot presented in the clock-location opposite the target in the search array. Observers were told that the target would always appear at the location opposite the cue.

Results and Discussion

The mean percentages of correct responses for the first target, averaged over lags, were 92.7% and 94.3% for the Cue and No-cue conditions, respectively. The mean DUR_c values for the second target at each lag are illustrated in Figure 4.3. An ANOVA

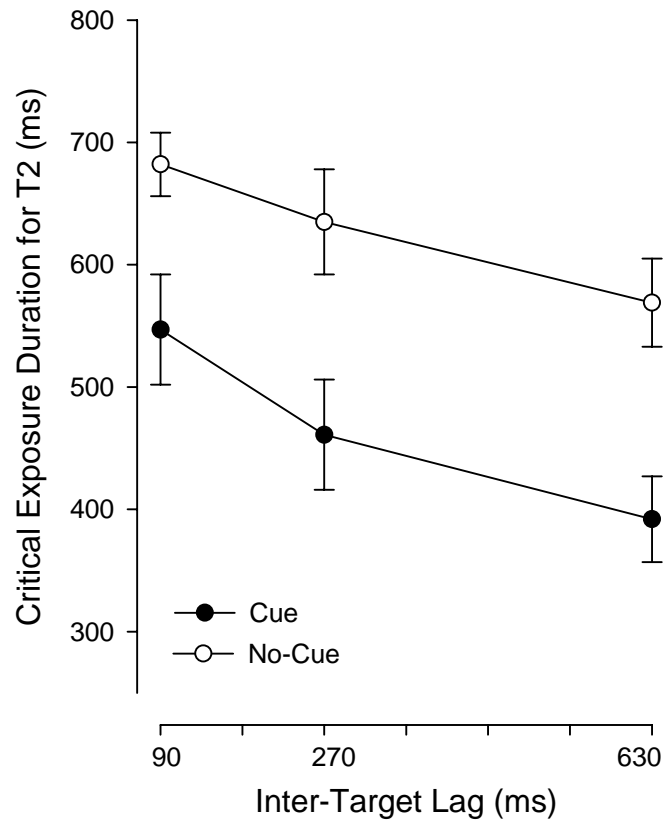
performed on the data in Figure 4.3 comprised two within-subjects factors: Cue (present, absent) and Lag (1, 3, 7). The analysis revealed significant effects of Cue, $F(1, 21) = 15.24, p = .001$, and Lag, $F(2, 42) = 11.06, p < .001$. The interaction effect was not significant, $F < 1$. The lowest individual DUR_c recorded in any of the six conditions was 77 ms, consistent with the absence of a floor effect.

As was the case in Experiment 4.1, much shorter exposure durations were required when the location of the second target was cued. Also, a significant AB deficit was in evidence, with the values of DUR_c decreasing as inter-target lag was increased. In contrast to the outcome of Experiment 4.1, however, the advantage conferred by the spatial cue was invariant with inter-target lag.

The main objective of Experiment 4.2 was to decide whether the reduced effectiveness of the cue at the shorter lags in Experiment 4.1 (Figure 4.2) arose from interference with the process of identifying the number-cue or from interference with the re-deployment of focal attention to the location denoted by the cue. The results strongly suggest that the interference arose not from the requirement to redeploy focal attention (which was in common to both experiments) but from the requirement to identify the spatial cue, which was unique to Experiment 4.1.

Figure 4.3. Results of Experiment 4.2. Bars represent the standard errors of the mean.

T2: Second Target; ms: milliseconds.



The finding that the values of DUR_c were invariant with inter-target lag (Figure 4.3) strongly suggests that attention could be redeployed without additional cost even while the system was busy processing the first target. On the tenets of additive-factors logic, this suggests that attentional redeployment and target identification are mediated by separate mechanisms that enable the two processes to be performed concurrently. From the perspective of the dual-pathway hypothesis, these results are consistent with the proposition that the cue and the target were processed along the dorsal and ventral pathway, respectively.

General Discussion

Earlier work has shown that the processes of spatial selection and identity extraction are separable (Ghorashi et al., 2009). A dual-pathway account of this separability was proposed in the earlier work on the assumption that the cue and the target were processed along separate visual pathways. The spatial cue (a dot denoting the location of the target within a search array) was said to be processed along the dorsal pathway whereas the target (a letter to be identified) was said to be processed along the ventral pathway. The principal objective of the present work was to examine some implications of this account. On the well-supported assumption (Ungerleider & Mishkin, 1982) that stimulus identification is carried out along the ventral pathway, the dual-pathway account would predict that independence should no longer be in evidence if both the cue and the target needed to be identified.

This prediction was supported in Experiment 4.1 in which the spatial cue consisted of a number that, once identified, denoted the location of the target within a circular search array. The effectiveness of the cue was impaired when it was presented while the hypothesized ventral-stream mechanisms were engaged in identifying a letter target. Experiment 4.2 tested whether that impairment was attributable to interference with the process of cue identification or with the process of redeploying attention to the location indicated by the cue. This was done by replacing the number-cue with a dot-cue presented at a location opposite that of the target in the circular array. This eliminated the need for cue identification but maintained the requirement to redeploy the attentional focus. The results strongly suggested that identification and attentional reorienting are

independent processes, thus implicating cue identification as the source of impairment in Experiment 4.1.

The present results have direct implications for models in which two sources of attentional control have been juxtaposed: voluntary (goal-directed; e.g., Folk & Remington, 1998) and automatic (involuntary, stimulus-driven; e.g., Theeuwes, 1992; 1993). A common requirement in Experiments 4.1 and 4.2 was to redeploy the focus of attention to a new location. In this sense, both experiments required some degree of goal-directed voluntary attentional control. Despite this commonality, the outcomes of the two experiments differed fundamentally from one another. It is likely that other factors, notably the requirement for cue identification, played a role. The pattern of results in Experiments 4.1 and 4.2 strongly suggests that the critical determinant of independence between cueing and the AB was not whether the control of attention was voluntary or automatic but whether or not the cue needed to be identified in order to redeploy the focus of attention.

From the perspective of the dual-pathway model advocated here, this means that cueing and the AB show evidence of interdependence only when the cue and the first target are processed along the same pathway. On this account, the evidence for interdependence obtained in Experiment 4.1 stemmed from the idea that both stimuli engaged common identification mechanisms along the ventral pathway. In contrast, in Experiment 4.2 the cue engaged dorsal-stream but not ventral-stream mechanisms, thus avoiding overlap with ventral-stream mechanisms engaged in identifying the first target, and yielding evidence for independence.

A strong version of the dual-stream model would predict that interdependence need not be limited to ventral-stream processing: it should also be in evidence if both the cue and the target were to engage common processing mechanisms along the dorsal pathway. A possible problem in testing this hypothesis might arise, however, if one considers the high rates of processing in the dorsal stream. Namely, it is possible that processing of the first target might be completed before the onset of the cue thus obviating any evidence of interdependence. Addressing this issue, however, would be beyond the scope of the present work.

Comparisons with related studies

The relationship between spatial cueing and the AB has been investigated by Zhang, Shao, Nieuwenstein, & Zhou (2008) who set out to determine whether endogenous (goal-directed) attentional control is impaired during the AB. The cue was an arrow presented in the centre of the screen, pointing to the location of the upcoming second target (a letter to be identified). Accuracy of second-target identification was higher in the cued than in the uncued condition. Importantly, the benefit conferred by the cue was invariant with inter-target lag. Zhang et al. interpreted this result as indicating that endogenous cueing is unimpaired during the AB. In support of the claim that arrow cues control attention endogenously, Zhang et al. reported that, when uninformative, arrow cues could be ignored. Yet, this claim is not undisputed. A substantial body of evidence strongly suggests that arrow cues exert attentional control exogenously (Hommel, Pratt, Colzato, & Godijn 2001; Ristic, Friesen, & Kingstone, 2002; Stevens, West, Al-Aidroos, Weger, & Pratt, 2008). This issue is obviously in need of further investigation.

At any rate, if arrow cues are regarded as exerting endogenous control, Zhang et al.'s (2008) findings would be inconsistent with the outcome of the present Experiment 4.1 in which endogenous cueing was shown to be impaired during the AB. This inconsistency can be resolved by invoking one of two assumptions. The first assumption is that arrow cues may be processed along the dorsal pathway if they are spatial indicators. This status could be the consequence of innate visual biases or through the acquisition of over-learned visual habits. The second assumption is that attention may be controlled in a goal-directed manner, not only for the non-spatial attentional functions governed by the ventral pathway, but also for the spatial functions subserved by the dorsal pathway. This assumption is consistent with Milner and Goodale's (1995) finding that dorsal-stream mechanisms can mediate goal-directed actions.

On either of these assumptions, the evidence for independence between cueing and the AB reported by Zhang et al. (2008) can be explained on the grounds that the arrow cue and the first target (a letter) were processed along separate pathways. From this perspective, Zhang et al.'s experiment is homologous to the present Experiment 4.2. Both experiments included elements of endogenous attentional control in that the focus of attention was redirected from the location of the cue to a new location. Notably, both experiments yielded evidence of independent processing. We suggest that both results can be explained on the same basis, namely, that the spatial cue was processed along the dorsal stream and the first target was processed along the ventral stream.

Zhang et al.'s (2008) conclusion that endogenous cueing is not impaired during the AB is also at odds with results reported in an electrophysiological study by Dell'Acqua, Sessa, Jolicœur, and Robitaille (2006) who concluded that endogenous

control of spatial attention is impaired during the AB. The dependent measure in Dell'Acqua et al.'s study was the amplitude of the N2pc (an enhancement of the posterior N2 wave at electrode sites contralateral to the target). The displays consisted of two concurrent RSVP streams of letter distractors, one on either side of fixation. Two pairs of targets were inserted in the stream: the first target was a pair of digits, and the second target a pair of outline squares – one coloured red, the other green – each with a gap on one side. The colour of the second target was pre-specified separately for each observer who reported which side of that square contained the gap. The results showed that the magnitude of the N2pc was drastically reduced when the second target was presented during the period of the AB.

This result fits nicely within the dual-pathway model advocated here, in which interdependence between cueing and the AB occurs when the cue and the first target are processed along the same pathway. The experiment of Dell'Acqua et al. (2006) did not contain an explicit stimulus cue. It did, however, require a discrimination between the two squares on the basis of colour. In this task, therefore, attentional control was clearly endogenous. When the second target was presented during the period of the AB, the colour discrimination had to be carried out concurrently with the identification of the first target. Considering that colour processing and identification of alphanumeric stimuli are carried out along the ventral pathway (e.g., Ungerleider & Mishkin, 1982), it follows that the first target and the defining feature of the second target were processed along the same pathway. Interference between the two processes during the period of the AB then followed, much as in the present Experiment 4.1.

Concluding comments

Are spatial selection and identity extraction separable processes? If what is meant by *spatial selection* is the process of redeploying the focus of attention, the evidence strongly suggests that it is separable from the process of identity extraction. The issue of separability becomes clouded, however, when spatial selection is manipulated by spatial cues that index the location of a target to be identified. In this case, the evidence can lead to a seemingly contradictory conclusion. Namely, if the cue itself requires identification along the same processing pathway as the target, then the results may point to interdependence. That interdependence, however, is caused by interference between two processes of identification, not between the processes of spatial selection and identity extraction.

This distinction was brought out in the present study by a juxtaposition of the outcomes of Experiments 4.1 and 4.2. In Experiment 4.1, the process of spatial selection was confounded with that of cue identification, producing the appearance of interdependence of spatial selection and identity extraction. That was not the case in Experiment 4.2, in which the cue did not require identification, thus disambiguating the processes of spatial selection and identity extraction, and producing clear evidence for their separability.

We conclude that spatial selection and identity extraction are separable in principle. Notably, this separability does not depend on whether attention is controlled exogenously or endogenously. Rather, separability follows from the idea that spatial selection and identity extraction are mediated by distinct underlying mechanisms.

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CHAPTER 5:

General Discussion

The principal objective of this dissertation was to examine whether attentional spatial selection and identity extraction are separable processes. One of the best examples of a basic task in which these two processes are usually combined is visual search. Most major theories of visual search talk about the order in which these two processes occur, but they leave the more fundamental question unanswered as to whether these two functions are separable. The first chapter of this dissertation examined extant theories of visual search in light of this fundamental question of separability. Therefore, this review is unique in looking at the theories of visual search from the perspective of separability of spatial and identity processing.

The first chapter revealed that in most visual search studies, the two processes of spatial selection and identity extraction were manipulated concurrently, making it impossible for those studies to answer the question of separability. For example, one of the factors that is manipulated most often is the number of distractors in a search array. While this manipulation increases the number of spatial locations where the target can potentially be presented, it also decreases the signal-to-noise ratio, which in turn impairs the process of identity extraction. To answer the question of separability of spatial-selection and identity-extraction processes, it is necessary to manipulate those two processes independently of one another in the same experiment. We began by developing a methodology to achieve this objective.

In the first study (Chapter 2), two experimental paradigms were used to influence the efficiency of spatial selection and identity extraction: exogenous spatial cueing, and

the attentional blink. Exogenous spatial cues have been used to study the deployment of attention to specific locations in a visual display (e.g., Eriksen & Hoffman, 1972). This is a manipulation that obviously influences spatial selection. The attentional blink (AB) is an impairment in the identification accuracy of the second of two targets inserted in a stream of distractors displayed in rapid serial visual presentation (RSVP). This second-target deficit is obtained when the temporal lag between the two targets is less than about 500 ms (Raymond, Shapiro, & Arnell, 1992). The AB is generally regarded as a high-level phenomenon that interferes with the process of identity extraction (Chun & Potter, 1995; Jolicoeur & Dell'Acqua, 1998).

In examining the separability of spatial selection and identity extraction, we adopted additive-factors logic in which it is assumed that processing is carried out in non-overlapping stages. If two factors influence independent stages, they will have additive effects on the dependent measure. Conversely, whenever additivity is found, the underlying mechanisms can be assumed to be independent (Sternberg, 1969). If, on the other hand, at least one of the factors influences both stages, an interaction between the two factors will be in evidence in the dependent measure; the underlying mechanisms can then be assumed not to be entirely independent. In three experiments, using additive-factors-logic, we demonstrated that spatial cueing and the AB showed additive effects on the response measure, and that, therefore, they can be regarded as affecting independent, non-overlapping stages of processing. In other words, it can be concluded that spatial selection and identity extraction are separable processes.

The second study (Chapter 3) was designed to deal with contrary evidence regarding the separability of location and identity processing. Nieuwenstein et al. (2005,

Experiment 4) used a methodology similar to that described in Chapter 2 but, contrary to the present results, found that the spatial cue affected performance differently depending on whether it was presented during the period of the AB or beyond it. Namely, the spatial cue facilitated performance when presented at short inter-target lags (i.e., during the AB), but it was ineffectual when presented at long lags (i.e., beyond the AB). The strong interaction that Nieuwenstein et al. obtained between spatial cueing and the AB is clearly at odds with our results in Chapter 2 and calls for an explanation. In our second study (Chapter 3) we showed how Nieuwenstein et al.'s experimental procedure produced an artefactual data-limitation ceiling that led to that specific pattern of results. By removing that ceiling, we showed that cueing and the AB do exhibit an additive relationship.

The experiment reported in Chapter 3 also provides suitable grounds for generalizing the conclusion of separability of spatial selection and identity extraction obtained in the first study (Chapter 2). In Chapter 3, we used the same paradigm as in Nieuwenstein et al. (2005, Experiment 4). Namely, instead of displaying the second target in a search array, two targets were presented one at a time at one of the four screen locations, with a mask presented after each target. On half the trials, a spatial cue (a “+” sign) was presented directly before the second target in the same screen location. Given that only one target was present on the screen at any given time, this paradigm did not involve visual search. The fact that the same pattern of results was in evidence in this experiment as in the experiments reported in Chapter 2 strongly suggests that the conclusion of separability of spatial selection and identity extraction is not limited to visual search.

In the final study (Chapter 4), we set out to test a prediction based on our interpretation of results in the first study (Chapter 2). In the first study, we accounted for the results by relating them to two major parallel pathways in primate vision: the dorsal and the ventral pathway. We argued that based on the characteristics of each pathway, it is plausible to assume that spatial cues (indexing the process of spatial selection) are processed along the dorsal pathway while the process of target identification is performed along the ventral pathway. Within this conceptual framework, spatial selection and identity extraction are separable because they are mediated by mechanisms that are anatomically and functionally distinct.

It follows from this line of reasoning that the independence of location and identity processing should no longer be in evidence if the spatial cue required processing mechanisms that were also required for processing the target. The results of two experiments supported this prediction, and also showed that when a spatial cue itself needs identification, it is the process of re-directing of attention – not the process of cue identification – that is independent from the process of target identification. Therefore, collectively, the results of the present studies (Chapters 2-4) strongly suggest that the processes of attentional spatial selection and identity extraction are separable functions.

Comparing results across experiments

All the experiments reported in this dissertation included a No-Cue control condition. They also included conditions in which spatial cueing was implemented in different ways, thus enabling a comparison of the effectiveness of the different cueing procedures. These experiments are uniquely suited for such comparisons because, with the single exception of a study by Olivers (2004), there is a dearth of cueing experiments

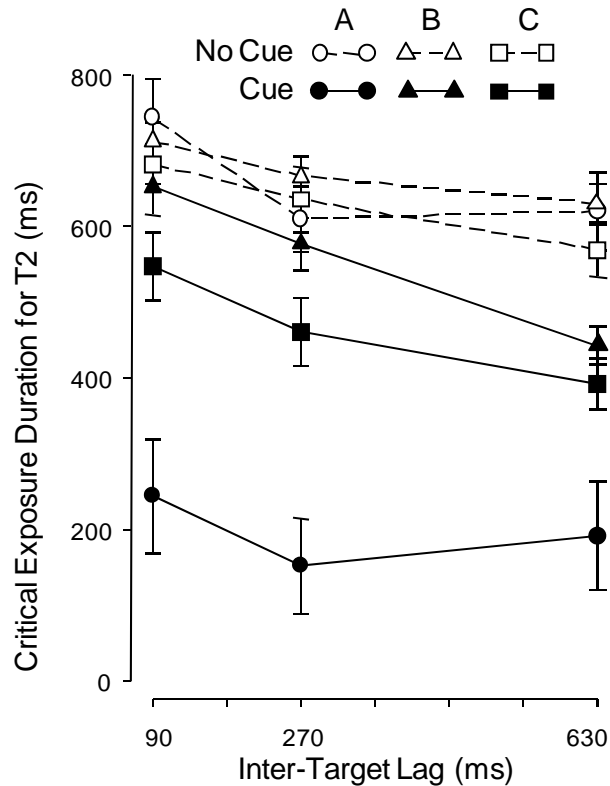
in the conventional visual-search literature. In addition, procedural details in Oliver's study make its suitability for such comparisons questionable. To wit, in that study there were multiple cues which were directly followed by pattern masks, and the SOA between the cues and the second target was in the order of 800 ms, compared to 90 ms in the present study. Because the cues had to be held in working memory, Oliver's study addressed the issue of spatial memory more than the issue of spatial selection examined here.

Three experiments in the present work lend themselves to cross-comparisons in that they shared the same dependent measure: critical exposure duration of the second target (DUR_c). Those experiments are Experiment 2.2, Experiment 4.1, and Experiment 4.2. The combined results are illustrated in Figure 5.1. For convenience and clarity, with reference to Figure 5.1, I refer to Experiment 2.2 as "A", to Experiment 4.1 as "B", and to Experiment 4.2 as "C". This denotation is used in the remainder of this chapter.

Several meaningful comparisons amongst the functions in Figure 5.1 suggest themselves. From Figure 5.1 it is clear that the results of the three No-Cue functions were very similar to one another. This is to be expected because they were mere replications of the same No-Cue condition in different experiments. Nevertheless, it is reassuring to note that performance in the No-Cue control conditions was not affected by the differences amongst the Cue conditions in the three experiments. A 3 (Experiments) x 3 (Lags) mixed between-within ANOVA carried out on the data for the three No-Cue conditions illustrated in Figure 5.1 revealed a significant effect of Lag, $F(2, 120) = 10.0$, $p < .001$. No other effects were significant (all F s < 1). Thus, the three No-Cue conditions exhibited an AB deficit, but did not differ in other respects.

Figure 5.1. Combined results from Experiment 2.2, Experiment 4.1, and Experiment 4.2.

Bars represent the standard errors of the mean. T2: Second Target; ms: milliseconds.



From Figure 5.1 it is also clear that there were substantial differences amongst the three Cue functions. A 3 (Experiments) x 3 (Lags) mixed between-within ANOVA carried out on the data for the three Cue conditions illustrated in Figure 5.1 revealed significant effects of Experiment $F(2, 60) = 20.1, p < .001$, Lag, $F(2, 120) = 17.0, p < .001$, and the Experiment x Lag interaction $F(2, 120) = 2.45, p = .05$. Two further comparisons among the functions in Figure 5.1 can shed light on the temporal dynamics of attentional processing.

Finding and processing the target

The time it takes to find the target in the search array, independent of the time it takes to extract its identity, can be estimated from a comparison of the Cue and No-Cue conditions in "A". Collapsed over lags, the mean $DUR_{c,s}$ in the Cue and No-Cue conditions were 196 ms and 658 ms, respectively. Comparisons between these means are justified by the non-significant interaction between Cue and Lag (see analysis in Chapter 2, Experiment 2.2). On the assumption that the cue-target SOA of 90 ms employed in the present work was sufficient to redeploy attention from central fixation to the cued location, the DUR_c of 196 ms indexes the time it takes to process the second target to an accuracy of 80% before the disruptive onset of the mask. On this reasoning, the difference of 462 ms between Cue and No-Cue conditions indexes the time taken in searching for the target – thus bringing the focus of attention to the target's location – in the No-Cue condition.

It is interesting to compare these estimates (which were based on a search display of set-size 12) with corresponding estimates obtained in an unpublished experiment in which the search display contained only six items. In most important respects, stimuli and procedures in that experiment were comparable with those in the present experiment. The mean $DUR_{c,s}$ in the six-item experiment were 213 ms and 466 ms for the Cue and No-Cue conditions, respectively. Whereas the $DUR_{c,s}$ for the Cue conditions were comparable in the two experiments (196 ms vs. 213 ms), the $DUR_{c,s}$ for the No-Cue condition differed substantially (658 ms vs. 466 ms). The longer DUR_c of 658 ms reflects the increased time taken to search a 12-item array relative to a 6-item array (466 ms). This comparison supports the reasoning, outlined above, that the 462-ms difference

in DUR_c between the Cue and No-Cue conditions in "A" (Figure 5.1) reflects the time taken in searching for the target in the No-Cue condition. This conclusion is supported further by the fact that the time taken to search individual items in the No Cue condition was approximately the same in the 12-item array (38.5 ms/item) as in the 6-item array (42.2 ms/item).

The time to re-direct attention

A comparison between the Cue conditions in "A" and "C" (Figure 5.1) permits an estimate of the time taken to re-direct attention from the location of the cue to the location of the target. The "A" (Cue) function in Figure 5.1 represents the results in the Cue condition in Experiment 2.2 in which the cue denoted the actual location of the target. The "C" (Cue) function in Figure 5.1 represents the results in the Cue condition in Experiment 4.2 in which the target was located at the clock location opposite the cue, requiring the observer to re-direct the focus of attention from the location of the cue to the location of the target.

The DUR_c for "A" (196 ms) plus the 90-ms cue-target SOA represents the time it takes to move the attentional focus from central fixation to the cue location plus the time it takes to identify the target to an accuracy of 80%. The DUR_c in "C" (467 ms) plus the 90-ms cue-target SOA includes the same elements plus the time it takes to redirect the attentional focus from the cue to the target. It follows that subtracting the DUR_c for "A" from the DUR_c for "C" will yield the time it takes to re-direct attention. This estimate of 271 ms is not unlike the estimate of approximately 250 ms reported by Weichselgartner and Sperling (1987) in a classical non-visual-search experiment in which observers were required to re-direct attention from the location of a cue to the location of the target.

The time to identify the number-cue

An estimate of the time taken to identify the number-cue in "B" can be obtained from a comparison of "B" and "C" on the assumption that the time taken to shift attention from central fixation to the location of the cue was approximately the same in "B" and "C". Although the separation between central fixation and cue location was marginally greater in "C" than in "B" (2.5° vs. 1.0° , respectively), the difference in "travel distance" can be regarded as negligible relative to the time taken by the processes of attentional disengagement and re-engagement (e.g., Posner & Raichle, 1994). On this assumption, "C" differed from "B" only in the requirement to identify the cue. The difference between the mean DUR_c for "B" (557 ms) and the mean DUR_c for "C" (467 ms) was 90 ms, which is an index of the time taken to identify the number-cue.

The above estimate of 90 ms was based on DUR_c s averaged over the three inter-target lags. But we have seen that cueing interacted with inter-target lag in "B" but not in "C" (Chapter 4). For this reason, it is prudent to calculate the above cue-identification time separately for each lag. On the finding that cue identification was impaired at the shorter lags (Experiment 4.1), correspondingly longer estimates of cue-identification time should be expected at the two shorter lags relative to Lag 7. The three cue-identification times (DUR_c "B" minus DUR_c "C") were 105, 116, and 51 ms for Lags 1, 3, and 7, respectively.

Two things are worth noting about these estimates. First, as expected, it took longer to identify the number-cue at shorter inter-target lags, at which the system was also engaged in identifying the first target. Second, the time taken for identifying the cue even inside the period of the AB (about 110 ms, on average) was substantially shorter

than the time required to redeploy attention from the location of the cue to the location of the target (about 270 ms; see preceding section).

Possible Limitations

The main argument in the present dissertation was predicated on additive-factors logic. On this logic, if two factors show additive effects, it is concluded that their underlying mechanisms are independent. By the same token, if two factors show multiplicative effects, it is concluded that they share at least some processing mechanisms. In experiments that reveal an additive relationship, a question might arise as to whether the inference of independence is tenable because it is based on a null result. With specific reference to the present work, a question might arise as to whether the absence of an interaction between the effects of cueing and inter-target lag reflects the independence of underlying mechanisms or a lack of power in the statistical analyses.

This concern can be addressed in four different ways that all converge on the same conclusion. The first approach is to note that the results of the three experiments in Chapter 2, the experiment in Chapter 3, and Experiment 4.2 in Chapter 4, all indicated main effects of both of the two main factors that were manipulated, with an additive pattern of these effects when they were combined (no hint of statistically significant interactions), pointing consistently to the separability of spatial selection and identity extraction. Thus, the evidence for additivity in the experiments considered collectively satisfy the minimal requirement for science, namely, that of replication.

The second approach is the one taken by Sternberg (1969) in his original development of the methodology. Noting that the absence of a statistical interaction in the additive patterns constituted a null result, Sternberg (1969, p. 287) said:

“Experimental artifacts are more likely to obscure true additivity of factor effects than true interactions”. In short, his argument was that random factors alone were much less likely to generate an additive pattern (one highly specific pattern) than they were to generate an interactive pattern (any one of which would violate the assumption of additivity). Seeing this pattern occur repeatedly in the different experiments stretches the credulity that this could have occurred solely through chance factors.

Third, it is extremely unlikely on the basis of conventional statistical reasoning that this result would reoccur in all five experiments reported here. In fact, if the α level is increased from 0.05 to 0.5 in order to decrease the probability of a type II error to an extremely low level (and thus increase the power of the test to detect a possible interaction), in four of five experiments the interaction would still be non-significant. The only experiment in which an α level of 0.5 would indicate a significant interaction would be Experiment 2.1 in which there was a chance of a floor effect, preventing a full additive pattern from being evident. Table 5.1 presents the η^2 calculated for each experiment that showed an additive pattern, and the post-hoc calculated power of each test for detecting a moderate (.4) effect, using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007), in each experiment.

Table 5.1. Calculated partial effect size and power for detecting a moderate effect (.4) for each experiment in which an additive effect was evident.

Experiment	η^2	Power
2.1	.147	.88
2.2	.046	.88
2.3	.057	.88
3.1	.001	.99
4.2	.016	.99

Fourth, the F -ratios for the interaction effects in four of the five experiments were < 1. This means that, on a post-hoc analysis based on the present pattern of results, and on the assumption that the F -ratio remains approximately the same, such an F -ratio would not be significant even if the number of subjects (the *degrees of freedom* for the denominator of the F -ratio) were unlimited. This would also be the case for the F -ratio of 1.9 obtained in Experiment 2.1, since this value is smaller than the critical F -value against which 1.9 would be compared given an infinite number of subjects [$F_{\text{critical}}(2, \infty) = 3.00$].

On the strength of these four arguments, we can be confident that the present experiments did not lack the necessary power, and therefore, that additive-factors logic was used appropriately to conclude in favor of real independence between the processes of spatial selection and identity extraction.

Contributions and Implications

Determining whether spatial selection and identity extraction act independently or interactively is important for both conceptual and practical reasons. Conceptually, a deeper understanding of this issue may lead to more comprehensive and veridical theories of visual search. For example, in the Guided Search model (Wolfe, 2006), which is one of the most detailed theories of visual search, there is no specific mention of the mechanisms that govern spatial guidance.

In that model, there is a general “guidance” stage that sends signals to the selective processes that lead to object recognition. In Wolfe's (2006) words, "The act of selection is mediated by a 'guiding representation', abstracted from early vision outputs" (p. 100). Attention is then said to be deployed to the locations containing specific attributes (e.g., colour, opacity, intersections) of the items in the guiding representation. What seems to be missing is a mechanism for guiding the focus of attention to those locations. In contrast, such a mechanism is provided within Feature-Integration Theory (Treisman & Gormican, 1988) by a "master map of locations".

Beyond behavioural theories of attentional control, the present studies have clear implications for neurophysiological theories. A case in point is provided by two conflicting views of the neuroanatomical structures and neurophysiological mechanisms that are involved in the endogenous (goal-directed) control of spatial selection and identity extraction. According to LaBerge (1997), the two functions are subserved by separate neural networks. Spatial selection is said to be mediated by mechanisms in the dorsolateral prefrontal cortex. In contrast, identity extraction is said to be mediated by

mechanisms in ventrolateral prefrontal cortex. On this scheme, voluntary control of spatial and identity processing is mediated by separate mechanisms.

An alternative scheme has been proposed by Corbetta and Shulman and their colleagues (Astafiev, Shulman, & Corbetta, 2006; Corbetta & Shulman, 1998; Corbetta et al., 2000; Corbetta & Shulman, 2002; Fox et al., 2006; Kindcade et al., 2005; Shulman et al., 2002) in which the voluntary control of the processes of spatial selection and identity extraction is said to be mediated by a common dorsal fronto-parietal network. The outcomes of the two experiments reported in Chapter 4 are consistent with the view that goal-directed spatial selection and identity extraction are independent processes. In this regard, the present conclusions of independence are clearly more in line with the proposals in LaBerge's (1997) model.

From a practical standpoint, knowing more about the mechanisms underlying spatial selection and identity extraction will help us improve proficiency in occupations such as air-traffic controlling and airport security-scanning that rely heavily on visual search. For example, knowing that spatial selection and identity extraction are separable functions leads to the inference that they might also provide the basis for different sets of skills that could be trained separately.

Future Directions

The results of the studies described in this dissertation open a number of avenues for future research. First, future research should be directed at finding out whether an AB deficit equivalent to that obtained with stimuli processed mainly along the ventral pathway also occurs with stimuli processed mainly along the dorsal pathway. Suppose, for example, that we perform a dual-task experiment in which both the first and the

second target involve dorsal-pathway mechanisms (e.g., identifying the direction of motion). It can then be asked whether the response to the second target is impaired when it is presented shortly after the first target. If so, what are the temporal characteristics of such an impairment? Considering the faster conduction rates in the dorsal pathway, the expectation would be that even if such an impairment were found, the duration of the impairment would probably be shorter than the equivalent AB in the ventral pathway.

Future research might also provide electrophysiological and brain-imaging evidence for the claim that spatial cues are processed along the dorsal pathway while target identity is processed along the ventral pathway. Functional magnetic resonance imaging (fMRI) is a suitable candidate because of its high spatial resolution. Magnetic encephalography (MEG) would be even better because it combines extremely high temporal resolution with reasonable spatial resolution. Specifically, MEG investigations might resolve the issue of whether the patterns of cortical activity generated by the stimuli and procedures used in the present work are more consistent with expectations based on the models of LaBerge (1997) or Corbetta and Shulman (2002).

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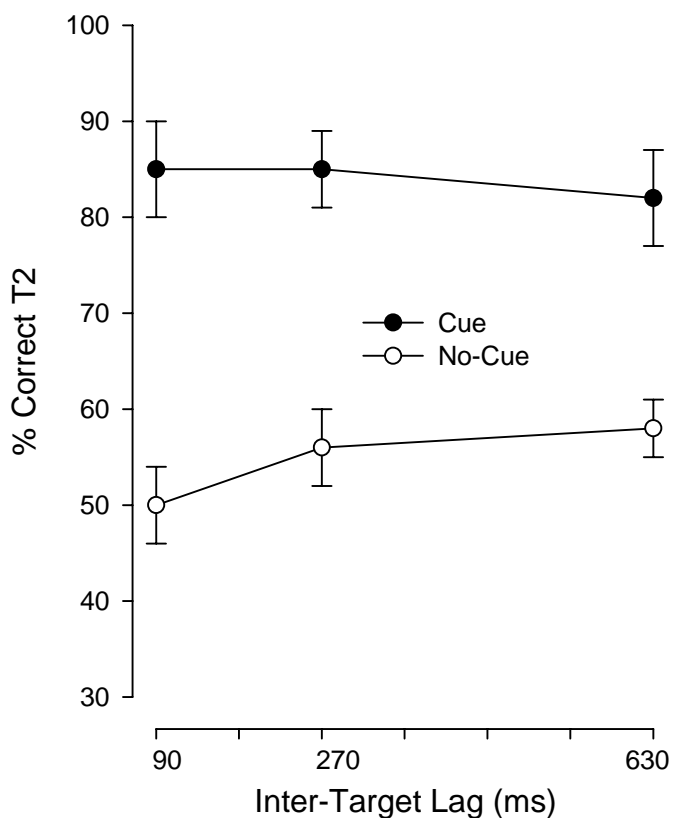
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APPENDIX 1

As a control, we also ran a single-task experiment in which the display, stimuli, and procedures were exactly the same as in Experiment 1, except that the observers were instructed to ignore every item displayed before the search array, and to perform only the search task. The results are presented in Figure 6.1.

Figure 6.1. Results of the single-task experiment. Bars represent the standard errors of the mean. T2: Second Target; ms: milliseconds.



The mean percentages of correct identification of the target at each lag are illustrated in Figure 6.1, separately for Cue and No-Cue conditions. An ANOVA performed on the data in Figure 6.1 comprised two within-subjects factors: Cue (absent, present) and Lag (1, 3, 7). The analysis revealed a significant effect of Cue, $F(1, 11) = 27.75, p < .001$. Neither the effect of Lag [$F(2, 22) = 1.20, p = .32$] nor the interaction effect [$F(2, 22) = 1.45, p = .26$] was significant.