# The alerting effect occurs in simple – but not compound – visual search

**by**

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## Abstract

Alerting (e.g., a brief flash preceding a target display) facilitates simple visual tasks that involve one step: locate a pop-out item within an array. It is unknown whether alerting facilitates compound tasks involving two steps: locate the pop-out item, then identify a detail of that item. I show that alerting facilitates each compound task component when tested separately, but not when combined. Yet, alerting facilitates compound tasks when the item reappears in the same location on successive trials. Such repetition may permit attention to linger at that location, allowing the first component to be bypassed. In practice, this turns the compound task into a simple task. That hypothesis was confirmed by using a re-orienting cue to shift attention to another location. An account of the absence of alerting in compound tasks is proposed in terms of the temporal relationship between an enhancement period and the sequence of visual processing stages.



**Keywords**: Alerting; visual search; attention; priming; compound tasks; temporal period of enhancement

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# Chapter 1. Introduction

*It turns out that an eerie type of chaos can lurk just behind a facade of order - and yet, deep inside the chaos lurks an even eerier type of order.*

*- Douglas Hofstadter, in Metamagical Themas*

Scientific theses often follow a conventional path where each step is methodically plotted and tightly regulated: a researcher uncovers a discrepancy in the literature, conducts an extensive literature review to identify the critical factors and potential confounds, formulates appropriate hypotheses, and then designs a rigorously controlled experiment to test the theory and to allow a straightforward interpretation of the results. However, there are times at which a researcher's supervisor may gaze quizzically upon the results and remark "Hm, isn't that odd…", incidentally derailing the previous research question and spawning an entirely new thesis project. The story of the present thesis is one of those times.

That initial, trajectory-altering study constitutes the first experiment reported in this thesis (see section 2.1). These confounding results suggest that *alerting*, a well-known effect in attention research, does not occur when the experiment involves a search task that requires multiple steps to complete. In contrast, the alerting effect is reliably obtained in tasks that can be completed in a single step. In fact, there were no publications to be found that investigated alerting in multiple-step tasks. To pursue this finding, a novel experimental paradigm was created, producing results for which the extant literature on attention had yet to account.

The current thesis draws from several literatures that are often treated as distinct but are - as will be made clear - complementary. The following chapters outline those theoretical and empirical considerations that are important for the current work. First, this chapter introduces the field of attention research. Following sections outline each of the literatures critical to the scaffolding of the thesis. In the final section, the surveyed evidence is brought together as the rationale for the thesis is presented.

## 1.1. Attention

As most students who have taken an undergraduate course in cognitive psychology are aware, *attention* is notoriously difficult to define (Di Lollo, 2018). One reason for this is that attention is not a unitary phenomenon, but rather a conglomerate of a varied interacting voluntary and involuntary cognitive and neural processes (Kahneman, 1973). Many definitions of attention have been suggested. One describes attention as the "cognitive resources, mental effort or concentration devoted to a cognitive process" (Galotti et al., 2017). Another explains attention to be: "the ability to focus on specific stimuli or locations" (Goldstein, 2018). While both definitions can be applied to attention, neither is able to aptly encompass the meaning of attention in its entirety. The former definition centers on attention's role in the allocation of neural energy towards different cognitive computations, while the latter treats attention as a para-perceptual process used to extract important information from the environment. Yet, there are other facets of attention that both definitions fail to encompass, such as the active suppression of irrelevant information (Hickey et al., 2009). In addition, the brain's attentional system is purported to be a group of networks that simultaneously are distinct yet constantly interacting with one another (Petersen & Posner, 2012). Though a precise definition remains elusive, William James (1890) once fittingly stated: "Everyone knows what attention is."

The difficulty in defining attention has led to the propagation of metaphors which act in substitute. Models based on such metaphors have been prolific in the field of attention research and continue to influence modern research directions. These metaphors should be taken as aids in the understanding of complex cognitive phenomena and not as descriptions of the underlying mechanisms themselves (for a recent commentary, see Di Lollo, 2018). That said, the two definitions provided in the above section each relate to different metaphors commonly used to discuss attention.

The first definition is inspired by the *finite resource* and the *glue* metaphors of attention. The finite resource metaphor champions the notion that attention is like an energy resource that can be allocated to cognitive tasks, but that its capacity is limited (e.g., Lavie, 2010). Regarding the glue metaphor, the influential Feature Integration Theory (FIT) describes attention to be a binding agent used to combine features of objects into a coherent representation (Treisman & Gelade, 1980).

The second definition is connected to such metaphors of attention as the *filter* and the *spotlight*. Filter models aim to demonstrate how information is selected to be attended while other sensory signals are ignored. Often regarded as the father of the filter model of attention, Broadbent (1958) thought that sensory stimuli were first funneled through a filter which identified the channels that should be attended while preventing irrelevant stimuli from passing through to working memory. Since then, others have modified the filter model significantly (e.g., Treisman, 1960; Deutsch & Deutsch, 1963; McKay, 1973). Although much of the work on filter models has employed auditory stimuli, the similar concept of the attentional spotlight evolved in the visual domain. Posner (1980) described visual attention as a beam of light that can be widened or focussed and can be directed across the visual field while the eyes are kept still. Processing in the region alit by the beam is enhanced relative to non-attended locations (Posner, Snyder, & Davidson, 1980). The spotlight metaphor is frequently encountered within an area of attention research called *visual search*, as detailed in the following section.

## 1.2. Visual Search

### 1.2.1. Searching for Features or Conjunctions

Imagine that you are searching for your car in a busy outdoor parking lot. You may know the general region where you had parked, but you may not recall your car's precise location. Complicating matters is the fact that cars generally share many common features. For instance, they typically have four wheels, a set of headlights, and windows, to name a few. Many cars may be the same colour, have similar accessories, and a few may even be the same model as your car. However, your car likely has a unique combination of those features. For example, let us assume that your car is a white Kia Rio with a kayak rack mounted on its roof. There is a good chance that your car is the only one with that particular feature configuration. Eventually, you see a car that has the correct combinations of features. You reach out with your car keys, and - to your relief - you hear the locks click open.

The above scenario is a simple example of visual search in the real world. In laboratory studies, visual search refers to a family of paradigms that require observers to search for a target object amongst a set of distractor objects (Wolfe, 2021). There are

two major types of visual search: *conjunction search* and *feature search* (Treisman et al., 1977; Treisman & Gelade, 1980). Of the two types, the parking lot scenario described above more closely resembles conjunction search. This kind of search tasks requires finding a target that has features in common with the distractor objects yet is the only object that has that particular combination of features. Feature search, on the other hand, involves finding a target that possesses a unique feature that is not shared by any other object in view. A more apt example of feature search requires some modification to the parking lot scenario. Consider searching for your car in a parking lot of other Kia Rio cars. All the other cars are blue, while yours is white. Your search quickly ends as your car seems to emerge from the scene almost instantaneously.

When comparing the two parking lot examples, the difference between conjunction search and feature search becomes clear. In feature search, individuals are required to detect a difference in a single feature, such as colour. In contrast, conjunction search involves identifying the correct combination of multiple features. Because different kinds of stimulus features are processed in separate brain regions, FIT proposes that attention is required in conjunction search to combine multiple features into a unitary percept (Treisman & Gelade, 1980; for updated accounts see Treisman & Sato, 1990, and Bouvier & Treisman, 2010). If the search display contains other objects that share some of the features of the target object, then the observer must attend to each object in a serial manner to determine whether that object is the target or a distractor. For this reason, conjunction searches are often described as “inefficient” (Wolfe, 2014). Evidence for such *serial search* behaviour comes from conjunction search studies that vary the number of distractors in a set (Wolfe & Horowitz, 2017). These experiments show that increases in set size lead to slower response times on average, indicating that observers take longer to find the target because there are more items to be searched. As the time taken to respond increases with the number of distractors, the graphical function defining this relationship is said to have a *steep* (or *positive*) *search slope* (Heinke & Humphreys, 2004; Wolfe & Horowitz, 2017).

A different relationship is observed with feature search. Feature searches are characterized by relatively shallow or *flat search slopes*: as the number of distractors varies in a feature search display, the average response times remain unchanged (Heinke & Humphreys, 2004; Wolfe & Horowitz, 2017; but see Lleras et al., 2020). If the density of items in the display is sufficiently high and focal attention is involved, then the

search slope function may become negative (Bravo & Nakayama, 1992). Feature searches are thus often referred to as “efficient” (Neisser, 2014; Wolfe, 2014). *Pop-out search* is often used as an analogous term in place of feature search (Maljkovic & Nakayama, 1994; Egeth, Jonides, & Wall, 1972). The term “pop-out” arises from the apparent saliency of the target. In pop-out search, the target is defined as the object in the display possessing a unique feature (e.g., the colour red), in contrast to the distractors which are homogenous along the same feature dimension (e.g., all coloured green). According to FIT, simple features of the display such as colour and orientation would be processed in *parallel* prior to the involvement of attention (Treisman & Gelade, 1980). Therefore, if a search target possesses a unique feature, such as colour, it immediately appears to the observer as the most salient object in view.

As is the case for other popular dichotomies in psychology, the strict delineation between serial and parallel forms of search is an outdated notion. Modern models aim to encompass both parallel and serial mechanisms into a single framework. The strongest of these models accommodate neuroanatomical and neurophysiological evidence of iterative re-entrant signalling mechanisms (Di Lollo et al., 2000; Bouvier and Treisman, 2010). Notably, Wolfe’s (2021) Guided Search model, currently in its sixth version, aims to reconcile key principles of Feature Integration Theory with the current visual search literature. Regardless of whether the task is a conjunction search or a feature search, Guided Search 6.0 models search as a dynamic two-stage process. Initially, certain features (e.g., colour, orientation) are processed in parallel. These stimulus-driven signals, along with observer goals, expectations, scene perception, and search history, feed into a *priority map* that is used to guide search. Visual regions are classified based on the likelihood that the target will appear at that location. The focus of attention then moves to those locations in order of decreasing priority until the search target is located.

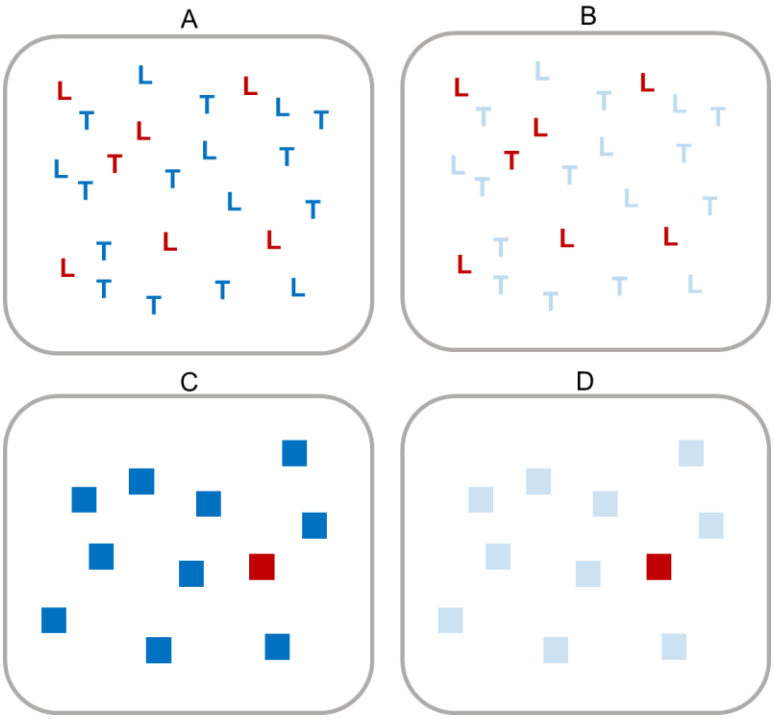


**Figure 1.1. Examples of the two major types of visual search.**
*Note.* Panels (A) and (C) are examples of conjunction and feature search displays, respectively. Panel (B) depicts how knowledge of the colour of a conjunction search target can be used to guide attention to high-priority objects (red) while ignoring the lowest-priority distractors (blue). The ignored distractors are portrayed as having decreased saturation relative to the high-priority items. As Panel (C) has but one oddly coloured item, attention is easily guided directly to the target, as portrayed in Panel (D).

Consider searching for a conjunction target such as a red T amongst blue Ts and red and blue Ls (see Figure 1.1A). Because the observer knows they are searching for a red letter, they do not need to search through blue letters. Guided Search 6.0 proposes that, consequently, those red objects will receive a higher priority than blue objects and will be searched through first (Wolfe, 2021). In Figure 1.1B the postulated priority of the red items is portrayed by desaturating the blue distractors. Compare that to an example of feature search (Figure 1.1C) where an observer looks for a uniquely coloured (e.g., red) square amongst square distractors of another colour (e.g., blue). Note that in the case of pop-out search, observers usually do not know the specific colour of upcoming target (i.e., there is an equal probability it will be either colour). In the feature search example, the target square is the only object that is of a different colour, resulting in a colour disparity confined to a particular location in the display. This disparity can inform the priority map that the target's location has the highest likelihood of containing the

target and, therefore, should be searched first. In Figure 1.1D the postulated priority of the red square is portrayed by desaturating the blue distractors.

### 1.2.2. Simple vs. Compound Search

Visual search tasks can be classified according to the number of processing steps required to determine the correct response. *Simple* visual search tasks are those that can be carried out in a single step. Duncan (1985) describes such tasks to be those in which knowledge of the features that distinguish the target from the distractors is sufficient to determine the correct response. For example, if participants are asked to decide whether a uniquely coloured object (i.e., the target) is present in a display with several objects that are all of a different colour, then the detection of a unique colour is all that is needed to answer correctly. The *brain state configuration* (i.e., the particular pattern of activity influenced by expectancy as well as recent experience) optimal for a simple task is thought to be already established at the time the visual system begins to process the search array (Di Lollo et al., 2001). In this case, enough information can be gathered to determine the correct response during this single stage, and no further processing is necessary. In contrast, *compound* search tasks are those that require two or more processing stages (Duncan, 1985). Compound search tasks themselves can be regarded as the combination of two simple tasks (Di Lollo et al., 2001). Taking the previous example one step further, a compound search task may require participants to locate the uniquely coloured target in the search display and then report a small detail of its shape.

Due to their nature, compound tasks necessitate an implicit *task-set reconfiguration*: a switch of one's mental set from a configuration initially tuned for the first step in the compound task (e.g., select the target from the array) to another configuration optimized for the second step (e.g., report the critical detail of the target's shape: Di Lollo et al., 2001). The explicit form of task-set reconfiguration is often studied using *task-switching paradigms* in which participants are presented with different tasks to perform from trial to trial (Rogers and Monsell, 1995). For example, participants may be presented with a digit and be tasked with indicating whether it is an even or an odd number. On the next trial, the task may change and participants must now report whether the digit is greater or less than 5. In this example, a task-set reconfiguration needs to be made from a mental set tuned optimally to the even-odd task to one tuned

optimally to the greater-or-less task. Depending on conditions, the process of task-switching can involve significant time costs, which include the time required for task-set reconfiguration (Hunt & Klein, 2002; Schneider & Logan, 2005).

We now turn to two effects typically associated with studies of visual search: *priming* and *alerting.*

### 1.2.3. Priming

Perceptual priming (henceforth referred to as *priming*) occurs when a feature of the target is repeated on successive trials. Priming is thought to be a form of implicit memory that interacts with attentional and perceptual processes (Schacter & Buckner, 1998). In visual search, priming refers to the finding that performance is enhanced when the critical feature of the previous trial's target is repeated compared to when it is changed. As reaction time (RT) is often the dependent measure in visual search, the priming effect illustrates that RTs are faster in the repeat condition. Compound search tasks have been frequently employed to study two effects of priming: *feature priming* and *location priming* (Maljkovic & Nakayama, 1994; 1996). Feature priming occurs when the repetition of a target's unique feature (such as colour) across successive trials results in faster response times as compared to when the unique feature is changed across trials (e.g., to another colour; Maljkovic & Nakayama, 1994; Fecteau, 2007). On the other hand, location priming occurs when the target is presented in the same location across consecutive trials, regardless of whether its defining feature changes value (Maljkovic & Nakayama, 1996). While these two types of priming are related conceptually, evidence suggests that they stem from independent underlying mechanisms (Ásgeirsson et al., 2014). A double dissociation between feature and location priming has been demonstrated using transcranial magnetic stimulation to inhibit two cortical areas in different brain regions, showing that there are unique brain regions involved in each type of priming (Campana et al., 2007; Campana et al., 2006).

Despite the numerous studies investigating priming, the precise mechanism underlying priming remains largely elusive. It has been proposed that priming facilitates the deployment of attention to similar targets (Maljkovic & Nakayama, 2000; Nakayama et al., 2004). Olivers & Meeter (2006) argue that the degree of ambiguity, either at any stage between stimulus encoding and response generation or in the definition of the task

itself, is the key determinant of the priming effect. Others suggest that it is later processing stages that benefit most from priming, such as response selection (Mortier et al., 2005; Theeuwes et al., 2006). Another option is that these accounts are not mutually exclusive, and that there may be both early and late priming effects (Töllner et al., 2008; Lamy et al., 2010). In line with this, it may be the case that no singular priming mechanism can account for all observed effects, as priming may occur at multiple levels within the cortical hierarchy (Kristjánsson & Campana, 2010; Kristjánsson & Ásgeirsson, 2019).

## 1.3. Alerting

*Alerting* refers to another facilitatory effect that is observed when a brief, task-irrelevant but perceptually salient stimulus precedes the onset of a visual display, resulting in faster RTs (Petersen & Posner, 2012). The alerting effect is revealed by comparing trials in which the alerting signal is present to those trials in which it is absent: when alerted, response times to the visual stimulus are shorter, thereby reflecting facilitated processing (Petersen & Posner, 2012). The alerting signal itself can be auditory (e.g., a tone; Bertelson & Tisseyre, 1969) or visual (e.g., briefly brightening the computer screen; Jefferies et al., 2021).

While this transient signal does not provide any predictive spatial information for the upcoming visual stimulus, it does enhance performance. It is thought that alerting stimuli cause facilitation by inducing a brain state that is prepared to receive incoming sensory information and may speed the orienting of attention to a relevant stimulus (Petersen & Posner, 2012). While the alerting effect is often described as a response speed advantage, evidence also suggests that perceptual sensitivity may be enhanced and that the beneficial effects may be reflected in accuracy measures (Kusnir et al., 2011). However, some experiments have demonstrated a speed-accuracy trade-off when the alerting stimulus is presented prior to the response display (Posner, 1978).

Several accounts of the alerting effect have been proposed and can be grouped into four types, depending on the stage of processing thought to be affected (Jepma et al., 2009). The account with the least support is that alerting facilitates processes of motor execution (e.g., Sanders, 1980; Sanders, 1983). However, electroencephalographic evidence shows that facilitation occurs prior to the onset of

response execution (Hackley & Valle-Inclán, 1998; Hackley & Valle-Inclán, 1999; Hackley & Valle-Inclán, 2003). Two other accounts suggest that facilitation involves decision-making processes. The first proposes that alerting affects the early stages of decision-making. Specifically, alerting may speed the rate at which evidence is accumulated towards one choice or another (Hackley & Valle-Inclán, 1999). The second account argues that instead of altering the rate of evidence accumulation, alerting lowers the decision threshold, thereby permitting decisions to be made with less available information, leading to the increased error rates observed in some experiments (Posner, 1978). More recent models argue against decision-making accounts, suggesting instead that facilitation occurs at stimulus-encoding stages (Jepma et al., 2009). The stimulus-encoding account, which has been referred to as the early-onset account, holds that the stimulus is encoded faster when it follows an alerting stimulus, thereby speeding the overall reaction time (Bernstein et al., 1970; Stein et al., 1996; Jepma et al., 2009; Tona et al., 2016; Nieuwenhuis & de Kleijn, 2013).

### 1.3.1. The Locus Coeruleus – Norepinephrine response

The *locus coeruleus* (LC) has emerged as a critical brain region underlying the alerting effect (Peterson & Posner, 2012). This small pontine nucleus is the brain's major source of norepinephrine (NE) and has diffuse projections throughout cortical and subcortical areas, with the notable exception that it does not project to the ventral visual stream (Aston-Jones & Cohen, 2005). It has been shown that phasic noradrenergic activity of the locus coeruleus is elicited by alerting stimuli and results in an increased signal-to-noise ratio of task relevant signals within thalamic and sensory cortical regions (Waterhouse & Navarra, 2019). In other words, because of phasic locus coeruleus activity triggered by an alerting stimulus, incoming sensory signals are enhanced relative to task-unrelated activity (i.e., to background noise; Mather, 2016).

### 1.3.2. Studying phasic alerting as an exogenous phenomenon

At this point, it should be noted that in the literature the term "alerting stimulus" has been used interchangeably with two other terms: "accessory stimulus" and "warning stimulus" (Hackley & Valle-Inclán, 2003; Lawrence & Klein, 2013). However, there is an important difference between accessory and warning stimuli, and this distinction hinges on the duration of the stimulus onset asynchrony (SOA) between the alerting stimulus

and the search display. By convention, the term “warning stimulus” is used when the SOA is greater than 500 milliseconds (ms). Alternatively, the term “accessory stimulus” is used when the SOA is shorter than 500 ms.

This distinction is not trivial, as accessory stimuli have been linked to exogenous (i.e., involuntary) mechanisms of attention, whereas the warning stimuli are thought to involve endogenous (i.e., voluntary, goal-directed) mechanisms (Lawrence & Klein, 2013). Endogenous attentional factors are known to operate on a longer time scale than exogenous factors (Hopfinger & West, 2006). In the case of alerting, endogenous factors introduce complexity, such as the accumulation of temporal expectation of the onset of the upcoming display (Lawrence & Klein, 2013). If the goal is to investigate the involuntary component of alerting on visual processing, as in the present work, then endogenous factors may obscure the interpretation of the results. Accordingly, specific design considerations were employed to minimize the endogenous attentional component (Lawrence & Klein, 2013). Therefore, the terms “alerting effect” and “accessory stimulus effect” will be treated synonymously, whereas “warning stimulus effect” is used to denote a different phenomenon and will not be discussed further.

## 1.4. Rationale

Substantial evidence was disclosed in the foregoing discussion that alerting facilitates simple search tasks. On the other hand, I was unable to find any studies that investigated the effects of alerting in compound search tasks. Thus, what is still unknown is whether alerting affects compound search tasks and, if so, whether the same alerting mechanisms affect performance in simple and in compound tasks. The first step towards that goal is to determine whether alerting occurs at all in compound search tasks. That was done in Experiment 1.

# Chapter 2. Experimental work

Presented in this chapter are the methods, results, and discussion sections of our paper titled “Alerting effects occur in simple – but not in compound – visual search tasks”, currently in press in Journal of Experimental Psychology: Human Perception and Performance.

## 2.1. Experiment 1

In Experiment 1, I adopted a paradigm first employed by Maljkovic and Nakayama (1994) to study the effects of *priming* (e.g., repeating the target item on successive trials; Kristjánsson & Campana, 2010). On any given trial, the display consisted of three diamond shapes, two green and one red, or vice-versa. Each diamond had a truncated left or right corner. Observers were required to indicate the side of the missing corner in the odd-coloured diamond.

That paradigm was used in the present work principally to study the effects of alerting, although priming was also examined. It should be noted that priming and alerting are known to differ in neurophysiological correlates. Priming is said to be subserved by a set of distinct mechanisms located at different levels in the visual system (Magnussen & Greenlee, 1999; Tulving & Schacter, 1990). In contrast, alerting is thought to depend on activation of the Locus Coeruleus – Norepinephrine (LC-NE) neuromodulatory system (Peterson & Posner, 2012). To induce a state of alerting, the entire screen was brightened briefly just before the onset of the diamond array, as was done by Jefferies et al., (2021) and by Jefferies & Di Lollo (2019).

### 2.1.1. Methods

#### *Observers*

One hundred and fifteen undergraduate students at Simon Fraser University served in the experiment for course credit. All had normal or corrected-to-normal vision. The data for 19 observers were excluded for having accuracy scores below 80%. All experiments reported in this paper received ethical approval from the Simon Fraser University Research Ethics Board.

### *Stimuli and procedures*

The basic display contained an array of three diamond patches (rotated squares). At a viewing distance of 57 cm, each diamond subtended 1° of width and height. On every trial, the array contained an oddball-coloured diamond designated as the target. On a random half of the trials the target diamond was coloured red and the remaining two were green; the colours were reversed on the remaining half of the trials. Either the left or the right corner of each diamond was cut off reducing the width to 0.85°. Observers were required to indicate as quickly as possible the side of the missing corner in the target diamond by pressing the Z (left) or the M (right) keys on the keyboard. The target diamond could occupy one of 12 possible locations around the perimeter of an imaginary circle of 10° diameter and was equally likely to appear in any of the 12 locations. The other two diamonds were displayed on the same perimeter, equidistant (i.e., 120°) from the target diamond and from each other (see Figure 2.1). The background colour was mid-grey (RGB 128), and a black fixation cross of 0.5° was permanently on view in the centre of the screen.

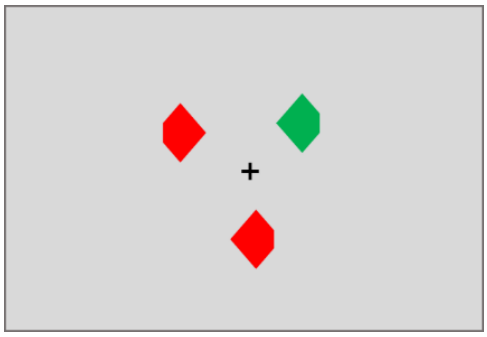

**Figure 2.1. Stimuli used in Experiment 1.**
*Note.* The colour oddball was green on 50% of the trials and red on the remaining trials. The screen background was mid-grey.

The experiment comprised of 12 practice trials followed by 768 experimental trials. Each trial began between 0.8 to 1.2 s, jittered randomly, following the response on the previous trial. During that interval, the display consisted of only the fixation cross. The stimulus array was then displayed and remained on view until response or for 2.0 s, whichever occurred first. On half the trials, an alerting stimulus was displayed consisting of the screen turning white for 48 ms. The screen then reverted to mid-grey and was followed 56 ms later by the stimulus array. The two factors (flash presence [2 levels] and target colour repetition [2 levels]), were fully crossed with one another. This resulted in a

total of 4 conditions. The experiment lasted approximately 45 min. The computer code and data files for all of experiments are accessible at: http://summit.sfu.ca/item/21283

### 2.1.2. Results and Discussion

In this and in all ensuing experiments the first trial in each block was not included in the analysis because, by its very nature, it could not be classified as either a “repeat” or a “change” trial. In all experiments, only the response times (RTs) for correct trials were included in the analysis. Also omitted from the analysis were outlier RTs that exceeded two standard deviations from the mean. In all analyses the Greenhouse-Geisser correction was applied whenever the assumption of sphericity was violated.

The mean accuracy across all conditions before exclusions was 90.7%, with scores ranging from 46.7% – 100%. A break in the distribution of scores occurred around 80%, which was well above the 50% chance level. So, I chose that as a threshold for rejecting scores below 80% from the analysis. That criterion level was applied in all experiments. The pattern of results was virtually unchanged whether the data included all scores or only the scores above the 80% criterion. This indicates that the inclusion of scores below 80% merely increased the level of noise in the analysis.

Following the exclusion of participants with accuracies below 80%, mean accuracy was above 95% in all experiments. Given this restricted range seen in Table A1, the accuracy results were not examined further. Error bars in all figures indicate 95% confidence intervals and were calculated according to the procedures outlined by Loftus and Masson (1994).

The results of Experiment 1, illustrated in Figure 2.2, were analyzed in a 2 (alerting flash: present/absent) × 2 (target colour: repeat/change) repeated-measures ANOVA. Consistent with Maljkovic and Nakayama’s (1994) finding that priming can occur in a compound search task with pop-out displays, the priming effect of colour repetition was significant (Figure 2.2a), $F(1, 95) = 462.81$, $p < .001$, $\eta_p^2 = .830$.

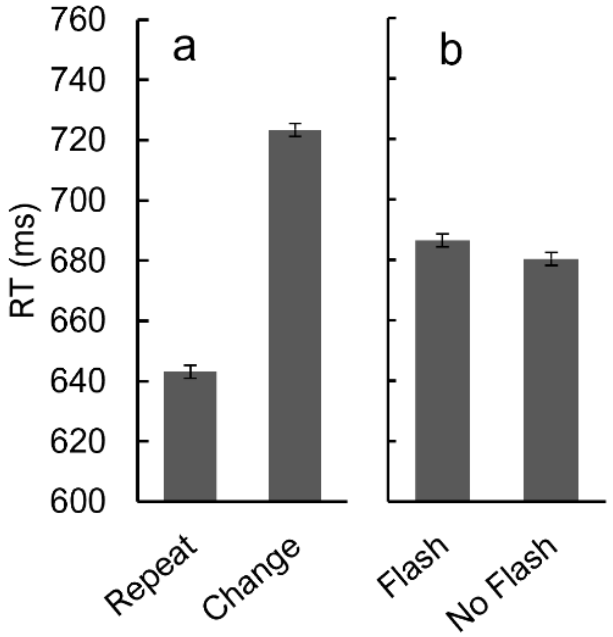


**Figure 2.2. Results of Experiment 1.**
*Note.* Panel (a): Effect of colour priming. RTs on trials in which the colour of the target was repeated from the previous trial were faster than on trials in which the target colour was changed. Panel (b): Effect of alerting. RTs were slightly but significantly longer in the Flash than in the No-Flash conditions. This is an unanticipated result in view of the conventional finding that alerted RTs are faster.

Based on earlier findings, I expected to obtain an alerting effect either as a main effect (Flash *vs* No Flash) or in the form of an interaction effect with priming (target colour repetition). The results disconfirmed that expectation. Not only was the interaction effect not significant, $F(1,95) = 0.40$, $p = .53$, but RTs were actually slower when the alerting stimulus was present than when it was absent (Figure 2.2b), $F(1, 95) = 7.88$, $p = .006$, $\eta_p^2 = .077$.

This anti-alerting effect deserves further investigation to confirm that it is not a Type-1 error. To that end, I used the Jeffreys' Amazing Statistics Program (JASP) to perform a Bayesian analysis comparing the null hypothesis of no difference between the Flash and No-Flash conditions (i.e., the numerator of the Bayes Factor, BF) against the hypothesis that the results of the two conditions differed from one another (denominator of the BF). The analysis revealed a BF of 5.06 which, according to Raftery (1995) is "positive" – as distinct from "weak" – evidence in favour of the null hypothesis. This Bayesian analysis strongly suggests that the anti-alerting effect revealed in the frequentist analysis may well be a Type-1 error. This issue may well deserve further

investigation. In the present context, however, the finding of principal interest was the absence of an alerting effect in a compound search task[1].

I pursued that finding in the ensuing experiments. In so doing, I was guided by the finding that alerting is known to occur in simple tasks (e.g., Spalek & Di Lollo, 2011; Fernandez-Duque & Posner, 1997). In Experiments 2a and 2b, I asked whether alerting occurs when the two simple components of the present compound task are examined individually.

## 2.2. Experiment 2a

In Experiment 2a I asked whether alerting occurs in a simple task that consists of the first component of the compound task used in Experiment 1, namely, finding the colour oddball in the search array.

### 2.2.1. Methods

#### *Observers*

One hundred and fifty undergraduate students at Simon Fraser University served in the experiment for course credit. All had normal or corrected-to-normal vision. The data for 32 observers were excluded, 25 for having accuracy scores below 80%, 5 for incomplete data files, and 2 for responding on over 25% of the catch trials.

#### *Stimuli and procedures*

Stimuli and procedures in Experiment 2a were the same as in Experiment 1, with the following exceptions. Ten percent of the trials were catch trials in which the display sequence contained only the alerting flash (i.e., the screen turned from mid-grey to white for 48 ms with no stimulus array)[2]. On half the non-catch trials, the array contained a colour oddball (e.g., one red and two green diamonds), with no oddball present on the

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[1] I thank Michael Masson for help with the Bayesian analyses.

[2] The catch trials were not directly relevant to the objective of Experiment 2a: they were a hold-over from an earlier pilot experiment.

other half of trials (e.g., all red diamonds). Fully crossed with these trials was the presence/absence of the alerting flash and the repetition/change of the target colour.

For ease of coding, successive trials were organized in pairs. On the first trial of a pair, the specific stimulus array was determined by the combination of factors being implemented (i.e., target presence/absence, target colour red/green, target alerted/not alerted). In practice, this was done by coding all 8 possible combinations of those three factors in a look-up table that was replicated 56 times which represents the number of trials to be run on each of the 8 combinations. On the second trial of each pair, the "target colour" factor was replaced by whether the colour of the target was to be repeated or changed from the previous trial. This also resulted in eight possible combinations (target presence/absence, target colour repeat/change, target alerted/not alerted) resulting in a total of 448 pairs of trials. Eighteen practice trials, two of which were catch trials, preceded the experimental trials.

The observer's task was to indicate whether or not the stimulus array contained a colour oddball by pressing a key on the keyboard. Half the observers pressed the *Z* key when the oddball was present and the *M* key when it was absent. The keys were reversed for the other half of observers. The experiment lasted approximately one hour.

### 2.2.2. Results and Discussion

For design reasons outlined above, the analysis contained only those oddball-present trials that were preceded by another oddball-present trial (a total of 112 possible trials). Those results, illustrated in Figure 2.3, were analyzed in a 2 (alerting flash: present/absent) × 2 (target colour: repeat/change) repeated-measures ANOVA. Responses were faster when the alerting stimulus was present (Figure 2.3b), $F(1, 117) = 10.53$, $p = .002$, $\eta_p^2 = .068$, and when the colour of the oddball was repeated on successive trials (Figure 2.3a), $F(1, 117) = 8.58$, $p = .004$, $\eta_p^2 = .083$. The interaction effect was not significant, $F(1,117) = 0.11$, $p = .75$.

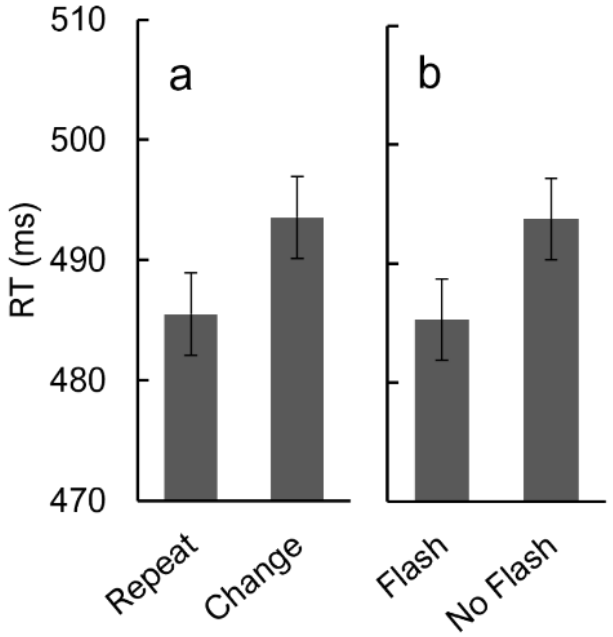


**Figure 2.3. Results of Experiment 2a**
*Note.* Panel (a): Effect of colour priming. RTs on trials in which the colour of the target was repeated from the previous trial were faster than on trials in which the target colour was changed. Panel (b): Effect of alerting. RTs were significantly faster in the Flash than in the No-Flash conditions.

A robust finding in the visual search literature is that alerting occurs in simple search tasks (Spalek & Di Lollo, 2011; Fernandez-Duque & Posner, 1997). The outcome of the present experiment is entirely consistent with that literature. Notably, this outcome is also consistent with the idea that the absence of alerting in Experiment 1 was not due to the nature of the first component of the compound task (i.e., finding the oddball in the stimulus array).

## 2.3. Experiment 2b

In Experiment 2b I asked whether alerting occurs in a simple task that consists of the second component of the compound task used in Experiment 1, namely, identifying the side of the missing corner of a diamond shape when it is the only stimulus on display. This design obviates the visual search inherent in the first component of the compound task, causing the second component to become a simple task.

### 2.3.1. Methods

#### *Observers*

Twenty-four undergraduate students at Simon Fraser University served in the experiment for course credit[3]. All had normal or corrected-to-normal vision. The data for 2 observers were excluded for having accuracy scores below 80%.

#### *Stimuli and procedures*

Stimuli and procedures in Experiment 2b were the same as in Experiment 1, except for the following. In order not to interfere with the perception of the target diamond, the fixation stimulus was changed to four L-shaped corners of an imaginary square of 2° side. The display consisted of a single diamond at centre screen. The task of the observer was to indicate the side of the diamond's missing corner. There were 128 trials in each of the four conditions in the 2×2 design, for a total of 512 experimental trials. These were preceded by 16 practice trials. There were no catch trials. The experiment lasted approximately 35 minutes.

### 2.3.2. Results and Discussion

The results, illustrated in Figure 2.4, were analyzed in a 2 (alerting flash: present/absent) × 2 (target colour: repeat/change) repeated-measures ANOVA. Responses were faster when the alerting stimulus was present (Figure 2.4b), $F(1,21) = 15.64$, $p = .001$, $\eta_p^2 = .427$. The effect of colour repetition was not significant (Figure 2.4a), $F(1, 21) = .21$, $p = .65$, $\eta_p^2 = .010$. The interaction effect was also not significant, $F(1, 21) = 2.83$, $p = .11$.

[3] Data collection in Experiment 2b was cut short by the onset of COVID 19, hence the reduced number of participants relative to the other experiments.

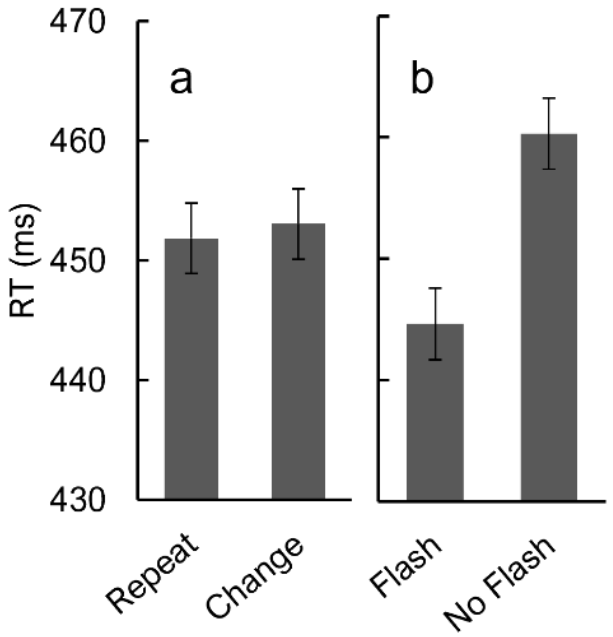


**Figure 2.4. Results of Experiment 2b**
*Note.* Panel (a): No colour priming was in evidence. RTs on trials in which the colour of the target was repeated from the previous trial were the same as on trials in which the target colour was changed. Panel (b): Effect of alerting. RTs were significantly faster in the Flash than in the No-Flash conditions.

As was the case for Experiment 2a, the outcome of Experiment 2b is consistent with earlier reports that alerting does occur in simple search tasks (Spalek & Di Lollo, 2011; Fernandez-Duque & Posner, 1997). Of direct relevance to the present work, the alerting effect obtained in Experiments 2b confirms that the absence of alerting in Experiment 1 was not due to the nature of the second component of the compound task (i.e., indicating the side of the diamond's missing corner).

It should be noted, at least in passing, that priming occurred in Experiment 2a but not in Experiment 2b. This is consistent with Kristjánsson, Saevarsson, and Driver's (2013) finding that priming requires visual search, which was the case in Experiment 2a (and in Experiment 1 where priming also occurred) but not in Experiment 2b. Given that the primary focus of the present work was on the effects of alerting, the presence of priming in Experiments 1 and 2a, and its absence from Experiment 2b, is not directly relevant in the present context, and is not examined further in the present work.

The critical question now becomes: Why was alerting found with the simple tasks of Experiments 2a and 2b, but not with the compound task of Experiment 1? Before

addressing this question directly, it is prudent to check on the generality of the pattern of results obtained in Experiment 1. To that end, I replicated the design of Experiment 1 with a different compound task, namely, the search task first described by Duncan (1985) and implemented by Theeuwes (1992).

## 2.4. Experiment 3

The basic design of Experiment 1 was replicated in Experiment 3 with the added provision that the location of the target was recorded across successive trials. This enabled an assessment of location priming as was done by Maljkovic and Nakayama (1996). In addition, the inclusion of location in the design permitted an assessment of the interaction between alerting and location priming.

### 2.4.1. Methods

#### *Observers*

One hundred and thirty-one undergraduate students at Simon Fraser University served in the experiment for course credit. All had normal or corrected-to-normal vision. Due to COVID 19 restrictions, data were collected remotely. Observers downloaded the program coded in Python onto their own Windows-based computer and followed the instructions on the screen. Of the initial 131 participants, 24 were excluded: five for colour blindness, four for incomplete data files, and 15 for having accuracy scores below 80%.

#### *Stimuli and procedures*

At the beginning of the experiment, a computer routine was run automatically which adjusted the stimuli to be of the same size across computers. The angular sizes of the stimuli were the same as in Theeuwes' (1992) study. Assuming a viewing distance of 57 cm, the angular sizes were as follows: the basic display consisted of six coloured rings each of 1.4° diameter located evenly on the perimeter of an imaginary circle of 6.8° diameter, beginning at 30° to the right of 12 o'clock. The background colour was mid-grey (RGB 128), and a black fixation cross of 0.3° was permanently on view in the centre of the screen. Each ring contained a line segment of 0.5° length, tilted 45° to the left or to the right, at random. On every trial, the array contained an oddball-coloured ring

designated as the target. On half the trials the target ring was coloured red; the remaining five rings were green. The colours were reversed on the remaining half of the trials. The target ring was displayed an equal number of times in each of the six locations. Observers were required to indicate as quickly as possible the tilt of the line inside the oddball ring by pressing the Z (left) or the M (right) keys on the keyboard.

The experiment comprised a total of 768 trials plus 10 practice trials. Each trial began between 1.0 to 1.5 s, jittered randomly, following the response on the previous trial. During that interval, the display consisted of only the fixation cross. The circular array was then displayed and remained on view until response or for 5.0 s, whichever occurred first. On half the trials an alerting stimulus was displayed consisting of the screen turning white for 48 ms, followed 56 ms later by the stimulus array. The sequence of events illustrated in Figure 2.7 applies also to Experiment 3, except that the white square used as a re-orienting event in Experiment 4 was replaced by a frame containing only the fixation cross in Experiment 3. The three factors (flash presence [2 levels], target colour repetition [2 levels], and target location repetition [6 levels]) were fully crossed with one another. This resulted in a total of 24 conditions. The experiment lasted approximately 45 min.

### 2.4.2. Results and Discussion

The results, illustrated in Figures 2.5 and 2.6, were analyzed in a 2 (flash) × 2 (target colour) × 6 (locations) repeated-measures ANOVA. The main effect of Flash was not significant, $F(1, 106) = 1.09$, $p = .30$. Responses were faster when the target colour was repeated from the previous trial than when it changed: $F(1, 106) = 557.91$, $p < .001$, $\eta_p^2 = .840$. Responses were also faster when the location of the target was repeated than when it was changed: $F(3.48, 369.13) = 101.95$, $p < .001$, $\eta_p^2 = .490$. The main effects of Colour and Location should be interpreted in light of the significant interaction effects of Colour × Location, $F(3.50, 371.22) = 3.84$, $p = .007$, $\eta_p^2 = .035$, and of Flash × Location, $F(4.71, 499.18) = 3.99$, $p = .002$, $\eta_p^2 = .036$.

#### *Examining the Colour × Location interaction effect.*

The essential aspects of the Colour × Location interaction effect are illustrated in Figure 2.5. The largest differences between Colour-Change and Colour-Repeat trials (i.e., the largest colour priming score) occurred not at Location 0 (i.e., the location at

which the oddball target was repeated on successive trials) but at Locations 1 and 5 which bracketed Location 0. This pattern of results gave rise to the significant Colour × Location interaction effect. Although an account of this unanticipated outcome does not come readily to mind, it certainly deserves further investigation. The principal focus of the present work, however, is on alerting. For that reason, that interaction effect is not examined further in the present work.

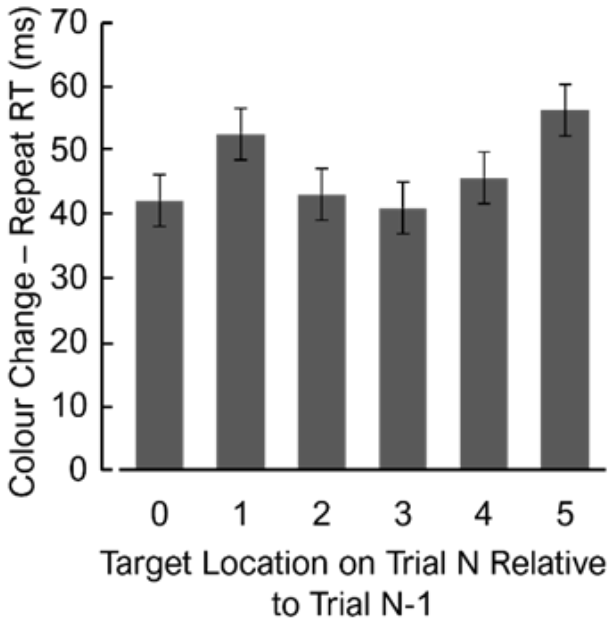


**Figure 2.5. Results of Experiment 3**
*Note.* Illustration of the Colour × Location interaction effect. Each bar represents the magnitude of the colour-priming effect, namely, the difference between two RTs: the RT in the colour-change condition *minus* the RT in the colour-repeat condition. The labels (0-5) represent the six possible locations in which the target on Trial N was presented relative to the target location on Trial N-1. The label "0" represents the case in which the target was displayed in the same location on both trials. The labels 1 and 5 indicate that on Trial N the target was displayed one position clockwise and counter-clockwise, respectively, relative to the position in which it had been displayed on Trial N-1. Similarly, the labels 2 and 4 indicate that on Trial N the target was displayed two positions clockwise and counter-clockwise respectively, relative to the position in which it had been displayed on Trial N-1. Label number 3 indicates that on Trial N the target was displayed in the location opposite that in which it had been displayed on Trial N-1.

### *Examining the Flash × Location interaction effect*

The Flash × Location interaction effect is illustrated in Figure 2.6. On the face of it, the interaction seems to be driven entirely by the RT difference between the Flash and the No-Flash conditions at Relative Location 0, namely at the "repeat" location. This was confirmed by a subsidiary ANOVA that did not include Location 0. In that analysis the

Flash × Location interaction effect was no longer significant, $F(4,424) = 0.07$, $p=0.99$. These analyses confirm that RTs were faster in the Flash than in the No-Flash condition at Relative Location 0 but not at any other location.

On the face of it, this pattern of results suggests that alerting can occur in a compound search task but only at the location at which the target is repeated on successive trials. That suggestion, however, runs afoul of the finding that alerting is a spatially nonspecific effect (e.g., Fernandez-Duque & Posner, 1997; Spalek & Di Lollo, 2011). If anything, the spatial specificity of the effect is more suggestive of the phenomenon of *attentional orienting* which is spatially specific (Fan et al., 2002; Fernandez-Duque & Posner, 1997). Besides differing in spatial specificity, alerting and orienting are known to differ in their neurophysiological correlates. Alerting has been associated with activation of the LC-NE neuromodulatory system (Posner & Petersen, 1990; Petersen & Posner, 2012). In contrast, orienting has been associated with activity in parietal cortex as well as other cortical regions (Petersen & Posner, 2012).

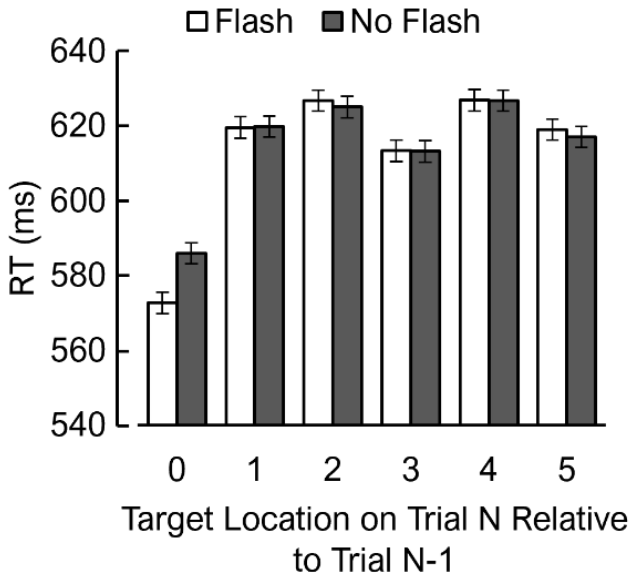


**Figure 2.6. Results of Experiment 3**
*Note.* Illustration of the Flash × Location interaction effect. The bars represent RT scores in the Flash (white bars) and No-Flash (black bars) conditions at each relative position. The meaning of "Relative Position" (0-5) is the same as in Figure 2.5. The Flash × Location interaction effect is driven entirely by the difference between the Flash and No-Flash conditions at Location 0. The corresponding differences at each of the remaining locations is close to zero.

An alternative account of the Flash × Location interaction may be proposed in terms of the maintenance of the focus of attention at Location 0 across trials. Suppose that on Trial N-1 attention is deployed to the target location and lingers at that location over the inter-trial interval. Then, if Trial N is a repeat trial, the target will land at an attended location, thus obviating the need for attention to be redeployed. The important consideration is that the maintenance of attention at Location 0 would bypass the first component of the compound task, namely, deploying the focus of attention to the location of the oddball. This would turn the compound task into a simple task consisting of its second component, namely, identifying the orientation of the line.

From this perspective, it can tentatively be claimed that alerting occurs in simple tasks but not in compound tasks. The ostensible evidence of alerting obtained in the present compound task on target-repeat trials (Figure 2.6) can be explained on the assumption that, on the trailing trial, the target landed at an attended location, thereby turning the compound task into a simple task. Experiment 4 was a test of that supposition.

## 2.5. Experiment 4

Experiment 4 was designed to test the hypothesis that the focus of attention lingered at the location of the target on the leading trial so that, on location-repeat trials, attention was already at the location of the trailing target. In this case, the task of spotting the oddball ring would be bypassed, and the line-orientation task would be performed as in a simple task. I reasoned that if the focus of attention could be diverted from the leading target's location, then the trailing target would no longer benefit from landing at an attended location, and the task would revert to a compound task. In Experiment 4 this was achieved by means of a re-orienting event similar to the procedure often used in studies of Inhibition of Return (e.g., Spalek & Di Lollo, 2007). Given this re-orienting procedure, I expected alerting to be no longer in evidence on Location-repeat trials. Specifically, I expected the Flash × Location interaction effect to be no longer significant.

### 2.5.1. Method

#### *Observers*

One hundred and three undergraduate students at Simon Fraser University served in the experiment for course credit. All had normal or corrected-to-normal vision. Due to COVID 19 restrictions, data were collected remotely. Observers downloaded the program coded in Python onto their own Windows-based computer and followed the instructions on the screen. Of the initial 103 participants, 22 were excluded: eight for incomplete data files, and 14 for having accuracy scores below 80%.

#### *Stimuli and procedures*

Stimuli and procedures in Experiment 4 were the same as in Experiment 3 with the single exception of an added re-orienting stimulus. The display sequence is illustrated in Figure 2.7.

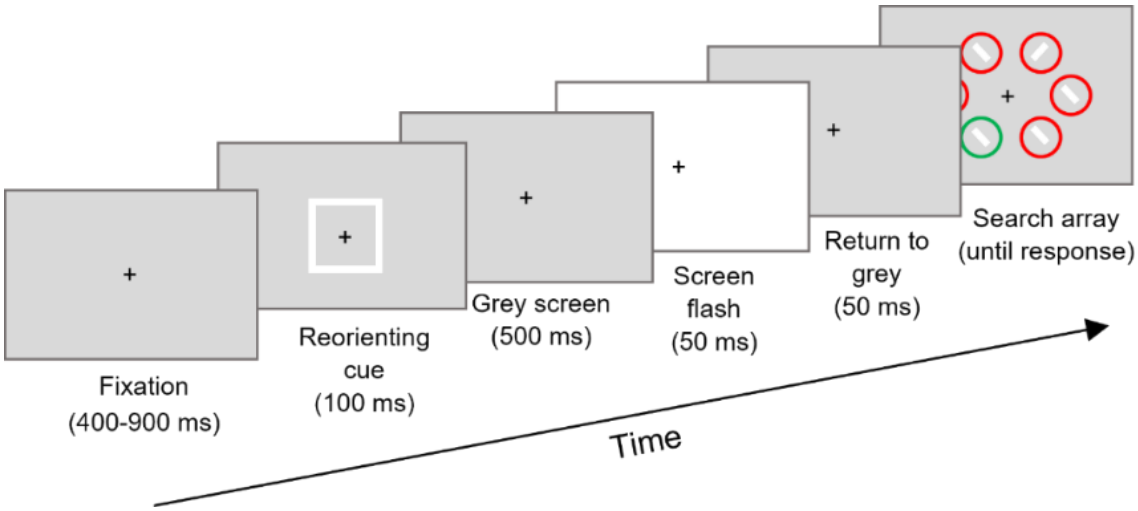


**Figure 2.7. Display sequence in Experiment 4**
*Note.* The alerting flash occurred on half the trials, but the re-orienting event (the white square outline) occurred on every trial at the location of the fixation cross.

Each trial began with the fixation cross for 400 to 900 ms. The re-orienting cue, consisting of a white square outline of 1° side, was then displayed for 100 ms. A blank 500-ms interval with only the fixation cross followed. On a random half of the trials, the alerting flash was then displayed for 50 ms and the screen returned to the fixation cross on a grey background for 50 ms. On the rest of the trials the screen remained unchanged for 100 ms. Finally, the search array was displayed and remained on the

screen until response, or 5s had elapsed, whichever was shorter. The experiment lasted approximately 45 minutes.

### 2.5.2. Results and Discussion

The results were analyzed in a 2 (flash) × 2 (target colour repetition) × 6 (locations) repeated-measures ANOVA. The main effect of Flash was not significant, $F(1, 80) = .54$, $p = .46$. Responses were faster when the target colour was repeated from the previous trial than when it changed: $F(1, 80) = 274.96$, $p < .001$, $\eta_p^2 = .775$. Responses were also faster when the location of the target was repeated than when it was changed: $F(5, 400) = 85.10$, $p < .001$, $\eta_p^2 = .515$. The main effects of Colour and Location should be interpreted in light of the significant interaction effect of Colour × Location, $F(4.17, 333.68) = 3.10$, $p = .014$, $\eta_p^2 = .037$. The Flash × Location interaction was not significant, $F(5, 400) = 1.08$, $p = .37$, $\eta_p^2 = .013$.

The outcome of principal interest is the non-significant Flash × Location interaction effect illustrated in Figure 2.8. Comparison of Figure 2.8 with the corresponding Figure 2.6 highlights the critical difference between Experiments 3 and 4 at Location 0, namely, the location at which the target was repeated across trials. Figure 2.6 shows that RTs were faster on Flash than on No-Flash trials (i.e., alerting occurred on location-repeat trials). This gave rise to the significant Flash × Location interaction effect. That is clearly not the case in Figure 2.8 where the RTs are the same on both Flash and No-Flash trials, thus precluding the interaction effect.

I attribute the difference between Figures 2.6 and 2.8 to the reorienting event which caused the focus of attention to be redeployed in Experiment 4. This caused the location at which the target had been displayed in the leading trial to be unattended on the trailing trial. The critical consideration is that in Experiment 4 the lack of attention at the repeat location no longer permitted the task to become a simple search based on only the second component. Instead, the task reverted to being a compound search that involved a switch in mental set from one optimally tuned to the first task (oddball detection) to one optimally tuned to the second task (line orientation).

In brief, the reorienting event prevented the first component to be bypassed (thus preventing the search from becoming a simple task) and caused the task to remain a

compound task. This pattern of results is in line with predictions based on the attention-lingering hypothesis, as outlined in the Discussion of Experiment 3 and in the Introduction of Experiment 4.

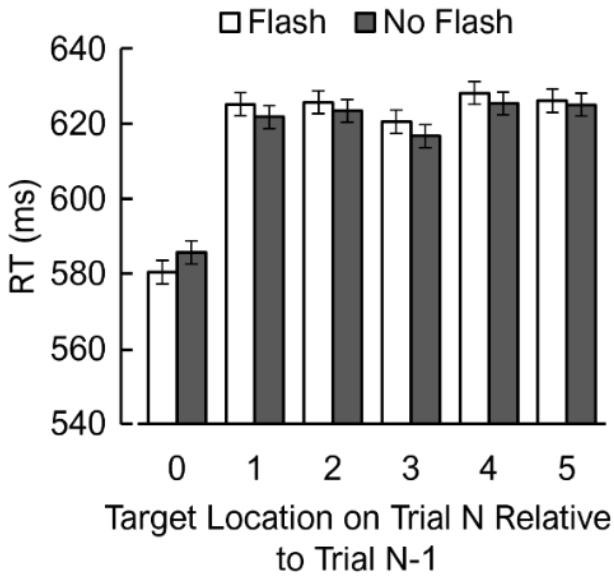


**Figure 2.8. Results of Experiment 4**
*Note.* Illustration of the lack of a Flash × Location interaction effect. The labels 0-5 have the same meaning as in Figure 2.5. The comparison of interest between Experiments 3 and 4 is with respect to Location 0, in which the target appeared in the same location on successive trials. Alerting (faster RTs at Location 0 on Flash trials) occurred in Experiment 3 but not in Experiment 4. This is consistent with the idea that the focus of attention lingered at Location 0 in Experiment 3 but not in Experiment 4.

It is of interest to note that the results of all experiments were consistent with the idea that priming and alerting are subserved by different mechanisms. With the exception of Location 0 in Experiment 3, alerting did not interact significantly with colour or location priming in any of the experiments. This would be consistent with Sternberg's additive-factors logic[4].

## 2.6. General Discussion

The primary finding in the present work was that alerting expedites performance in simple but not in compound search tasks. To be more precise, alerting occurs in

[4] I thank Roberto Dell'Acqua for suggesting the connection with Sternberg's additive-factors logic.

compound tasks only on trials in which the target is presented in an attended location, thus effectively converting the compound task into a simple task. The next step is to speculate on the determinants of these outcomes.

Two ways in which alerting may enhance performance in visual-search tasks have been distinguished in the literature. One is to enhance processing at a specific stage: motor execution (e.g., Sanders, 1980, 1983), decision-making (e.g., Hackley & Valle-Inclán, 2003; Posner, 1978), or stimulus-encoding (e.g., Bernstein et al, 1970; Tona et al., 2016). The second way is to enhance processing not at a given stage but for a specified temporal period. For example, an attentional component akin to alerting has been studied by Nakayama and Mackeben (1989) who regarded it as a transient attentional response that facilitates the processing of ensuing stimuli for up to about 200 ms. The “processing stage” and the “temporal period” hypotheses make different predictions about the effect of alerting in compound tasks. The two accounts are considered separately below.

### 2.6.1. Predictions from the processing-stage account

The processing-stage option can account for the presence of alerting in simple tasks, but not for their absence in compound tasks. Indeed, it predicts that alerting occurs not only in simple but also in compound tasks. The processing-stage account is illustrated in Figure 2.9, in which the two constituent tasks are labeled “Task 1” and “Task 2”. Each processing stage is rendered as a box whose length corresponds to the duration of the process named inside the box. The critical detail in Figures 2.9(a) and 2.9(b) is the duration of Task-1 processing. Processing is expedited when the sequence begins with an alerting stimulus (Figure 2.9(a)), but not when there is no alerting stimulus (Figure 2.9(b)). This results in faster processing of Task 1 which permits an earlier initiation of Task 2. The gain in processing speed should be reflected in shorter RTs on alerted trials. But that is not what I found. Rather, RTs were much the same in the Flash (alerting) and in the No-Flash (no alerting) conditions. This outcome clearly disconfirms predictions from any of the processing-stage accounts discussed above.

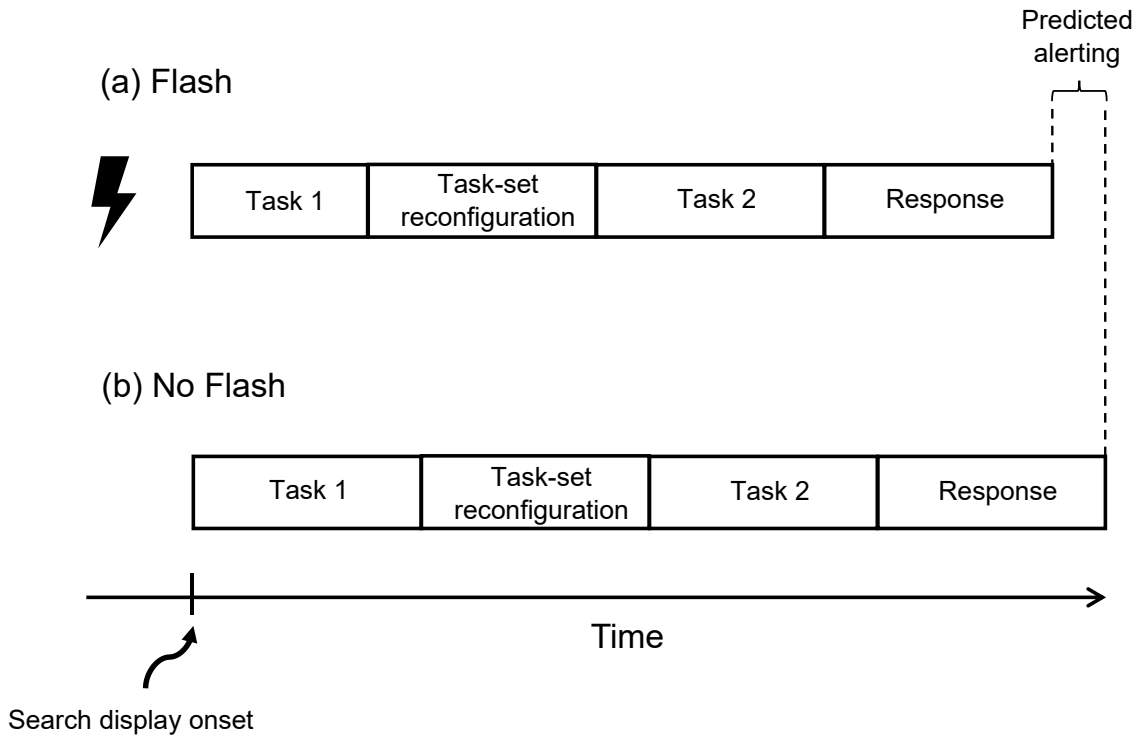


**Figure 2.9. Stage-dependent accounts incorrectly predict faster RTs on alerting trials**

*Note.* Sequence of processing stages during compound search as instantiated in stage-based accounts. (a) sequence of events on Flash (alerted) trials. The lightning bolt represents the alerting stimulus. (b) sequence of events on No-Flash (non-alerted) trials. See text for details.

### 2.6.2. Predictions from the temporal-period account

The temporal-period hypothesis – illustrated in Figure 2.10 – can account for both the presence of alerting in simple tasks and for its absence in compound tasks. As in Figure 2.9, the two constituent tasks are labeled “Task 1” and “Task 2”, and each stage is rendered as a box whose length corresponds to the duration of the process named inside the box.

An important consideration for compound search tasks is the degree of enhancement over time. RTs are known to decline rapidly as SOA between the alerting stimulus and the search display is increased to approximately 200 ms (Bertelson & Tisseyre, 1969; Müller-Gethmann et al., 2003; Lawrence & Klein, 2013). Further increments in SOA result in corresponding increments in RT to asymptote. The temporal progression of the enhancement can be modelled as an *ex-Gaussian* function illustrated in Figure 2.10. Such a pattern of enhancement is consistent with theories based on the

locus coeruleus - norepinephrine (LC-NE) neuromodulatory system which also exhibits an ex-Gaussian-like function of NE release (Usher et al., 1999).

Sudden stimuli trigger phasic activation of LC and enhance performance for a brief period following an alerting signal (Beane & Marrocco, 2004). Phasic activity in LC peaks about 100 ms after stimulus onset and endures for about 100 ms before giving way to a refractory period lasting up to about 400 ms (Nieuwenhuis et al., 2005; Usher et al., 1999).

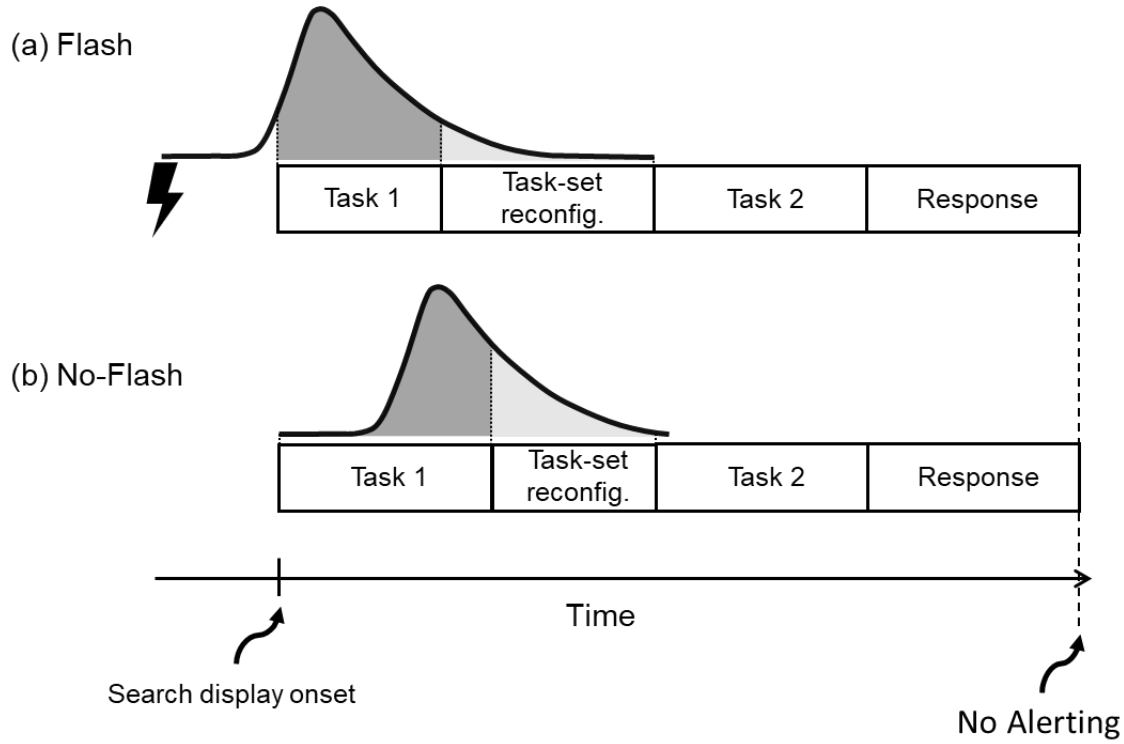


**Figure 2.10. Temporal-period account predicts the absence of alerting in compound tasks**

*Note.* The lightning bolt represents the alerting stimulus. Stimulus-processing stages are illustrated as boxes with text labels. Degree of enhancement over time is conceptualized as an ex-Gaussian function. See text for details.

Crucial to the temporal-period account is the overlap between the period of enhancement and the timing of the two components of the compound task: oddball detection (Task 1 in Figure 2.10) and task-set reconfiguration. This overlap is illustrated in Panels (a) and (b) of Figure 2.10. Each panel has two parts: the degree of enhancement as a function of time, modeled by the ex-Gaussian function, and the sequence of task-related processing events (outline boxes). The degree of enhancement

due to the overlap is represented by grey shading: dark grey for Task 1; lighter grey for task-set reconfiguration. The overriding consideration is that the period of enhancement is triggered by two separate events: the onset of the flash in the Flash condition (Panel (a)) and the onset of the search array in the No-Flash condition (Panel (b)). The difference in the timing of the triggering events provides a basis on which to account for the presence of alerting in simple tasks and for its absence in compound tasks.

In both panels of Figure 2.10, the process of task-set reconfiguration begins after the processing of Task 1 has been completed. The overlap between the stages of processing and the enhancement function is critical. In Panel (a) the overlap with Task-1 processing is substantial but is less extensive with task-set reconfiguration. In contrast, in Panel (b) the temporal overlap is smaller with Task 1 but larger with task-set reconfiguration. This causes Task 1 to be performed faster in the Flash condition (Panel (a)), and the reconfiguration to occur faster in the No-Flash condition (Panel (b)). This is illustrated by showing the Task-1 box as slightly shorter in Panel (a) and the Task-Set Reconfiguration box as slightly shorter in Panel (b). I hypothesize that the relative amount of speeding-up is approximately equal for Task 1 in the Flash condition and the task-set reconfiguration in the No-Flash condition, leading to comparable RTs in the Flash and No-Flash conditions.

### *Alerting in simple tasks*

Because simple tasks do not include a process of task-set reconfiguration, their temporal relationship with the period of enhancement can be expressed in terms of the temporal overlap between the ex-Gaussian enhancement function and Task 1, as illustrated in Panels (a) and (b) in Figure 2.11. The overlap is clearly more extensive in the Flash condition (Panel (a)) than in the No-Flash condition (Panel (b)), causing Task 1 to be performed more rapidly in the former. This is the conventional alerting effect (Fernandez-Duque & Posner, 1997), and is illustrated in Figure 2.11 by showing the Task-1 box as slightly shorter in Panel (a) than in Panel (b).

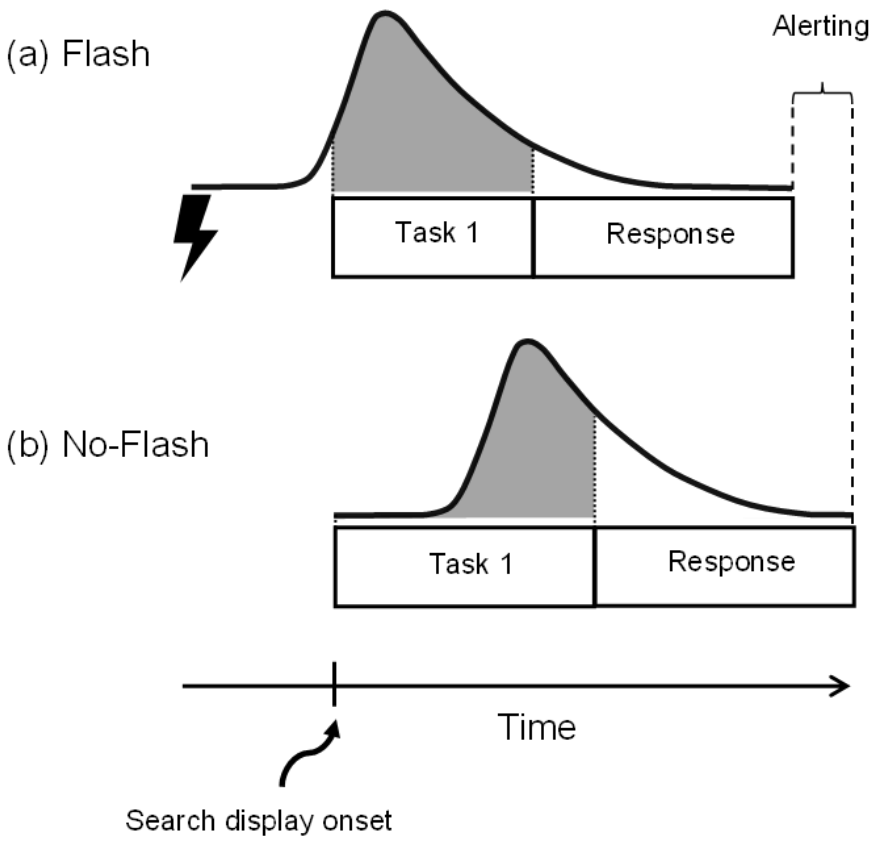


**Figure 2.11. Alerting in simple tasks**
*Note.* The lightning bolt represents the alerting stimulus. Stimulus-processing stages are illustrated as boxes with text labels. Degree of enhancement over time is conceptualized as an ex-Gaussian function. See text for details.

# Chapter 3. Supplementary Analyses

The experimental outcomes are consistent with the idea that the alerting effect does not occur in compound search tasks. In addition to the primary analyses reported in the previous chapter, two supplementary analyses of data from Experiments 3 and 4 were conducted to further probe the *attention-lingering hypothesis* first proposed in section 2.4.2. First, Experiment 3 data were reanalyzed to investigate a possible Flash × Location interaction when the current target's location was repeated from two, not one, trials prior. The outcome of this analysis is consistent with the present thesis. Second, a potential link between Autism Spectrum Disorder (ASD) and the Flash × Location interaction is explored. This prospective link spawns new research questions and considerations for future experimentation.

## 3.1. Reanalysis of the Flash × Location interaction in Experiment 3

The major finding from Experiment 3 was that alerting does not occur in compound search tasks unless the location of the target on Trial N-1 is repeated on Trial N (see Figure 2.6). It was hypothesized that the focus of attention lingered at the location of the previous target during the inter-trial interval. The reappearance of the target in the same location precluded the need to re-orient attention to the target, effectively reducing the compound task to the single step of determining the line's tilt.

However, the possibility remained in Experiment 3 that the alerting effect at Location 0 was not due to such a transitory mechanism as attentional lingering. Rather, it could be the consequence of an interaction between alerting's enhancement processes and the lasting implicit memory trace of the previous target's location (i.e., location priming). Indeed, the dorsal visual stream receives input from the LC-NE system (Morrison & Foote, 1986) which contains sites that have been implicated in location priming (Kristjánsson et al., 2007). But based on the primary analysis of Experiment 3 alone, it is not possible to distinguish between the two interpretations.

A differentiation between the two explanations – the attention lingering and the enhancement of location priming hypotheses – is possible if one considers an important feature of the location priming effect: its duration. The RT benefit resulting from the

repetition of target location endures for some time, often reported to be extinguished after approximately five to seven trials (Maljkovic & Nakayama, 1996). If the Flash × Location interaction in Experiment 3 results from an enhancement of location priming, then such an interaction should also be present when examining location priming effects carried over from two trials prior (i.e., repeating the target's location from Trial N-2 on Trial N). On the other hand, if there is no evidence of a Flash × Location interaction, then it is the attention-lingering hypothesis that garners support.

To differentiate between the two interpretations, the data from Experiment 3 were re-analyzed to evaluate this interaction when the target location on Trial N was either repeated or changed from that of the target on Trial N-2. Trials were excluded if the intervening trial (i.e., Trial N-1) had the same target location of either Trial N or Trial N-2 (i.e., it was a "repeat" trial). Otherwise, the analysis mirrors that of Experiment 3 (see section 2.4.2).

### 3.1.1. Results and Discussion

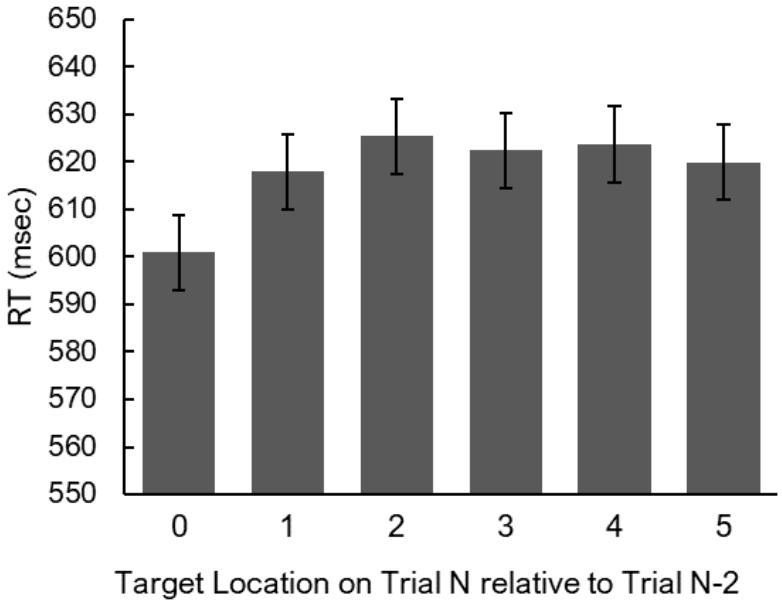


**Figure 3.1. Significant carry-over location priming from Trial N-2**
*Note*. Location priming effects carried over from two trials back. Location 0 indicates that the target location on Trial N-2 was repeated on Trial N, whereas the other values (1 – 5) indicate that the target appeared in a different location.

The results from Experiment 3 were analyzed in a 2 (flash) × 2 (target colour) × 6 (locations) repeated-measures ANOVA. The main effect of Flash was not significant, $F(1, 106) = .02$, $p = .89$. Responses were faster when the target colour was repeated from the previous trial than when it changed: $F(1,106) = 151.67$, $p < .001$, $\eta_p^2 = .59$. Responses were also faster when the location of the target was repeated than when it was changed: $F(4.23,448.8)=22.97$, $p < .001$, $\eta_p^2 = .58$. Importantly, the Flash × Location interaction was not significant: $F(3.6, 383.78) = .44$, $p = .76$. Similarly, the remaining interaction effects failed to reach significance.

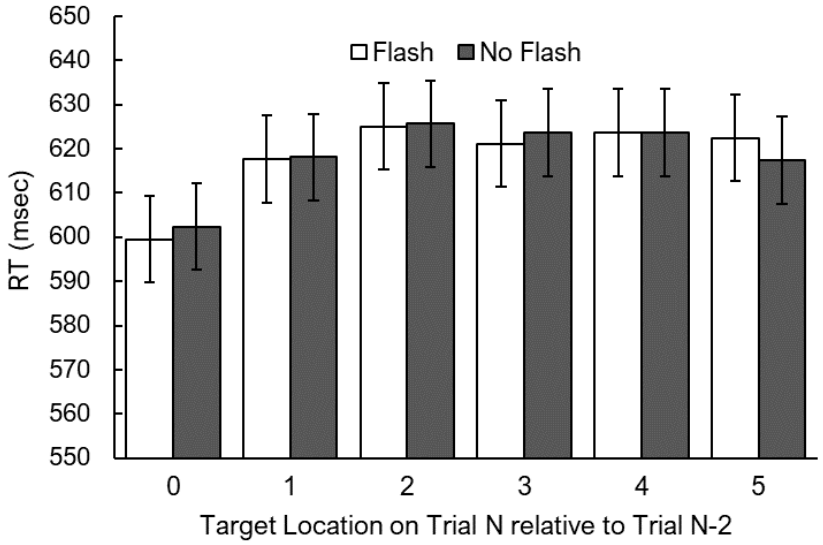


**Figure 3.2. No Flash × Location interaction when target location repeats from Trial N-2**

*Note*. No RT differences between Flash and No-Flash trials across relative target locations.

Critically, these results disconfirm the location-priming enhancement hypothesis of Experiment 3. Although there were significant location priming effects carried over from Trial N-2, these effects were not facilitated by the alerting stimulus on Trial N. In contrast, the attention-lingering hypothesis readily explains these results. It is worth noting that the intervening trial (i.e., Trial N-1) was always a “change” trial. This is because the restriction on the data to be analyzed eliminated trials in which the location of the target on Trial N-1 was repeated. Consequently, attention could not linger at the location of the target on Trial N-2 because the intervening trial necessitated a shift in attentional focus to the new target’s location. For the same reason, Trial N was always a “change” trial relative to Trial N-1. Thus, even though the location of the target on Trial N-2 remained primed on Trial N, there was a requirement to shift the focus of attention to

the location of the current target. Therefore, it was necessary to perform both steps of the compound search task on Trial N, resulting in no Flash × Location interaction. The attention-lingering hypothesis was confirmed in a subsequent study with the addition of an inter-trial attentional re-orienting cue (see section 2.5 and Figure 2.8).

## 3.2. Reanalysis of the Flash × Location interaction Experiment 4: Autism Quotient Questionnaire

Attentional deficits are often reported in the ASD literature. For example, individuals with ASD may demonstrate difficulties with attentional flexibility, including orienting and disengaging attention (Keehn et al., 2013). Different patterns of LC activation have been found for ASD individuals as compared to the neurotypical population (Bast et al., 2018). To check on the role of ASD-related attentional deficits, Autism Quotient (AQ) questionnaires were administered to participants in Experiments 3 and 4. The AQ questionnaire is a series of 50 statements which probe characteristic traits commonly exhibited by individuals with ASD (Baron-Cohen et al., 2001). AQ scores of 32 or higher indicate a high likelihood of ASD. While there was no apparent difference between individuals with high and low AQ scores in Experiment 3, a curious pattern of results emerges in Experiment 4 regarding the difference between Flash and No-Flash trials when the target location was repeated across successive trials (i.e., the Flash × Location interaction).

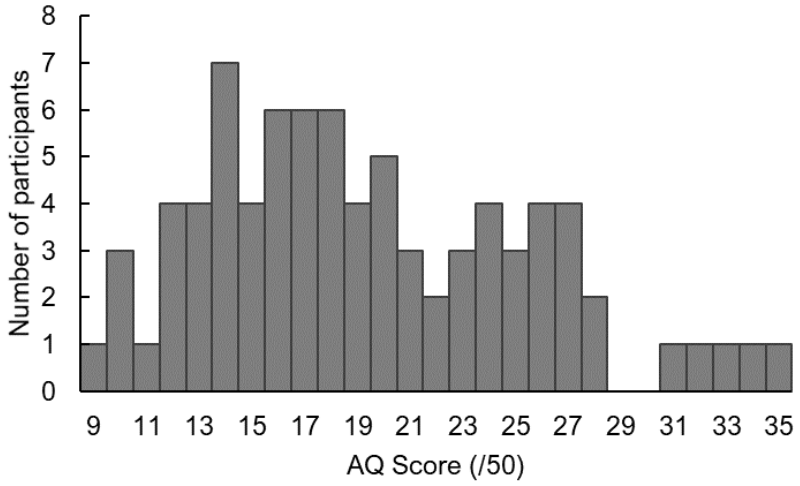


**Figure 3.3. Distribution of participant AQ scores in Experiment 4**
*Note.* Distribution of AQ scores of Experiment 4 participants. Higher scores indicate a higher probability of ASD.

Although the Flash × Location interaction in Experiment 4 was not statistically significant, there was a small numerical difference between the Flash and No-Flash conditions at Location 0 (see Figure 2.8). This difference appears to be driven mainly by those participants with AQ scores greater than 30. For these highest scorers (n = 5), the average response times for Location 0 were notably faster on Flash trials (591 ms) relative to No-Flash trials (641 ms). In contrast, this difference was negligible (2 ms) for those with AQ scores below 30 (n = 76). I hypothesized that this difference in alerting arose from the exogenous re-orienting cue failing to capture the attention of the high-AQ scorers.

Unfortunately, the range of AQ scores was restricted ([9 – 35]), and the distribution was positively skewed, as shown in Figure 3.3. Nonetheless, a possible interaction between AQ scores and the Flash × Location interaction was investigated. The data of Experiment 4 were split into equal tertiles ($n_i$ = 27) based on AQ score. This resulted in three groups: Low-AQ (score range: [9 – 16]), Mid-AQ ([16 – 21]), and High-AQ ([22 – 35]). I hypothesized a three-way interaction between AQ Group, Flash, and Location, with the High-AQ group being the primary driver of the effect.

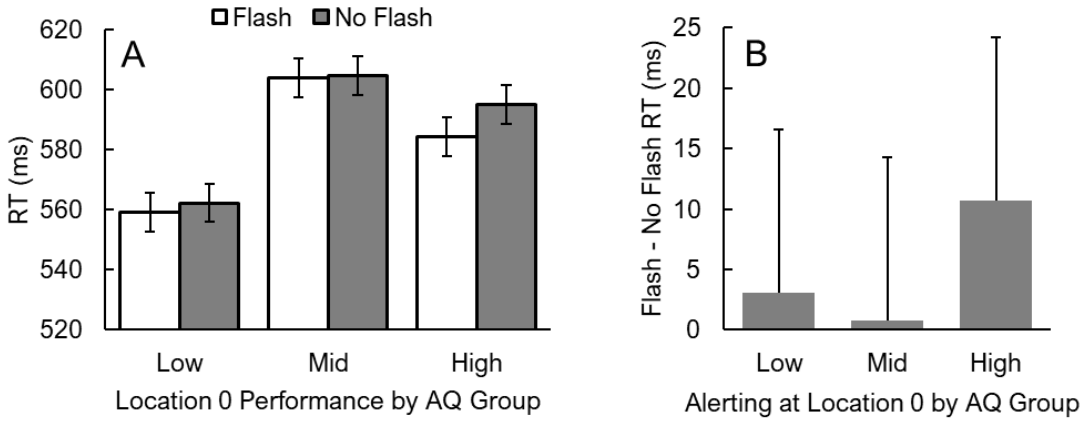


**Figure 3.4. Examining Flash vs. No-Flash RTs at Location 0 between Low-, Mid-, and High-AQ scorers**

*Note.* Panel (A): Results comparing AQ group differences on Flash and No Flash RT performance on trials in which the target location was repeated from the previous trial (i.e., Location 0 trials). Error bars indicate 95% confidence intervals calculated according to the within-subjects procedures outlined by Loftus and Masson (1994). Panel (B): RT difference scores between Flash and No Flash trials when the target location was repeated from the previous trial. Error bars indicate 95% confidence intervals for between-subjects comparisons. Note difference in vertical scales between (A) and (B).

### 3.2.1. Results and Discussion

The results from Experiment 4 were re-analyzed in an ANOVA with 2 (flash) × 2 (target colour) × 6 (locations) within-subjects factors and AQ Group as a between-subjects factor (3 levels: Low-AQ, Mid-AQ, and High-AQ). Of primary interest, the Group × Flash × Location interaction (Figure 3.4A) was not significant, $F(10, 390) = .84$, $p=.59$. Therefore, no difference in the Flash × Location interaction was detected across AQ groups.

I believe this observation warrants further investigation. Two obvious factors impacted the present analysis. First, the distribution of AQ scores resulted in the under-representation of participants with high AQ scores. Even in the High-AQ group, only 5 out of 27 scores were above 30. Thus, any between-group differences may have been washed out by the tertile grouping. Second, the design of Experiment 4 was not adequate for addressing this specific research question. For example, the number of trials per Location may have been inappropriate for a between-subjects comparison, causing the statistics to be underpowered. In section 4.1, I propose a future experiment designed to probe this possible AQ group difference in the Flash x Location interaction. The proposed changes will permit a more adequate investigation of alerting during compound search in individuals with ASD.

# Chapter 4. Future Directions

The present thesis provides a satisfactory answer to the question of whether alerting occurs in compound search tasks. The experiments suggest several new research questions. Two of these questions are of particular theoretical importance and are detailed in turn below.

## 4.1. ASD and the Flash × Location interaction

In a supplementary analysis of Experiment 4 (see section 3.2), I noted that those participants who scored highest on the AQ questionnaire (i.e., greater than 30, n = 5) showed faster RTs on Flash trials when the location of the target was repeated. Meanwhile, those with scores lower than 30 did not show a difference in RTs between Flash and No-Flash trials at any Location. I hypothesized that the exogenous re-orienting cue may have failed to capture the attention of the high-AQ scorers, because of their deficit in disengaging attention (Keehn et al., 2013).

While the outcome of the supplementary analysis did not show any between-AQ Group differences, I identified two major factors likely impacting the analysis (detailed in section 3.2.1). First, there were very few participants in the sample who had high AQ scores. To address this, participants can be recruited based on their AQ score data and grouped into Low (e.g., [0-16]), Mid (e.g., [17-33]), and High (e.g., [34-50]) AQ groups. This will ensure that the entire range of AQ scores is represented while maintaining equal sample sizes across groups. To ensure appropriate statistical power, a sample size of 36 participants per AQ group (total N=108) is required (analysis conducted using G*Power, *v.* 3.1.9.4).

Second, the experiment was not designed adequately to explore between-group differences. To address this, two changes can be made: (i) decrease the number of locations within the search array to four, so that 25% of the time the target location will repeat from the previous trial and 75% of the time it will change, and (ii) increase the number of trials per condition. This will increase the number of trials per Flash x Location condition to 92, thereby improving the estimate of the relevant RT scores. These changes permit a better investigation of the mechanisms of alerting during compound search tasks in those individuals with ASD. In this way, the outcomes of the basic

research reported in the present thesis may extend to clinical populations with impacted attentional functioning. Understanding how alerting affects performance in tasks of higher complexity can lead to novel insights in both neurotypical and neurodivergent populations.

## 4.2. Varying the SOA between flash and search array

Another avenue for future work could test predictions from the model described in section 2.6.2. The relationship between the period of enhancement and the sequence of processing stages proposed in that model hinges on the SOA between the flash and the search array. For example, increasing the SOA would alter fundamentally that relationship. This is illustrated by comparing Figure 4.1 (long SOA) with the corresponding panel in Figure 2.10 (short SOA). It is essential that the longer SOA in the proposed experiment be within the range of SOAs appropriate for alerting to be regarded as exogenous (i.e., less than about 300 ms; see section 1.3.2 and Lawrence & Klein, 2013).

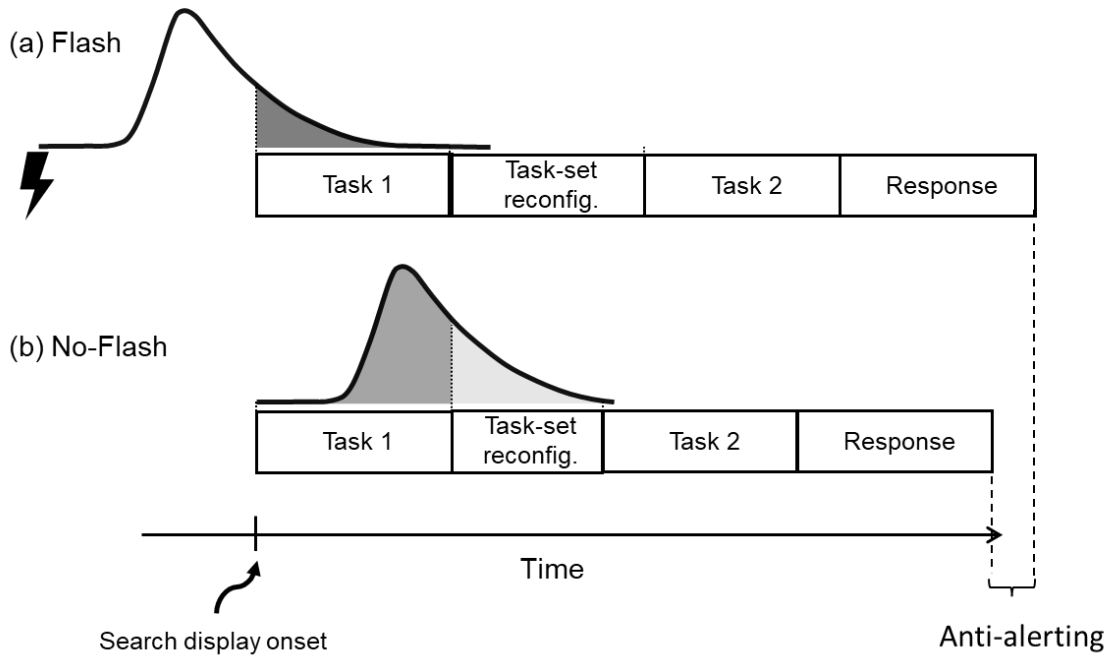


**Figure 4.1. Temporal-period account predicts anti-alerting when increasing SOA between the flash and the search array.**
*Note.* This figure is the same as Figure 2.10 except that the SOA between the flash and the search array is longer the present figure.

The model illustrated in Figure 4.1 predicts slower RTs on Flash relative to No-Flash trials. This is because when the flash precedes the onset of the search array by approximately 200 ms, there is substantially less overlap between the enhancement function and Task-1 processing stages, leading to relatively less facilitation on Flash than on No-Flash trials.

In addition, this model predicts that RTs on Flash trials will increase gradually as a function of the SOA between the flash and the search array. This could be investigated by varying the SOA systematically between 50 and 250 ms. I expect that, at short SOAs, there will be no alerting effect. However, as the SOA increases, a growing anti-alerting effect may be in evidence.

## 4.3. Concluding comments

What can be concluded regarding the main question asked in the present work, namely, whether alerting occurs in compound search tasks? Based on the present findings and the account illustrated in Figure 2.10, it can be confidently asserted that alerting does not occur in compound search tasks. This is because a period of enhanced processing in compound search tasks is triggered by different elements of the display: the onset of the flash in the Flash condition; the onset of the search display in the No-Flash condition. This facilitates different processing stages in the Flash and No-Flash conditions, eventually yielding comparable RTs. By the same token, this account is consistent with the mechanisms of alerting in simple visual search, illustrated in Figure 2.11.

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# Appendix. Table for reaction time and accuracy data

| | Alerting | Colour | Location | RT (ms) | ACC (%) |
|---|---|---|---|---|---|
| **Experiment 1** | | | | | |
| | Flash | Repeat | - | 646 | 96.7 |
| | | Change | - | 727 | 95.6 |
| | No Flash | Repeat | - | 641 | 96.5 |
| | | Change | - | 720 | 95.4 |
| **Experiment 2a** | | | | | |
| | Flash | Repeat | - | 481 | 95.4 |
| | | Change | - | 490 | 94.6 |
| | No Flash | Repeat | - | 490 | 95.3 |
| | | Change | - | 497 | 95.0 |
| **Experiment 2b** | | | | | |
| | Flash | Repeat | - | 442 | 96.4 |
| | | Change | - | 447 | 96.7 |
| | No Flash | Repeat | - | 462 | 96.3 |
| | | Change | - | 495 | 96.0 |
| **Experiment 3** | | | | | |
| | Flash | Repeat | 0 | 551 | 96.5 |
| | | | 1 | 592 | 95.5 |
| | | | 2 | 606 | 95.5 |
| | | | 3 | 590 | 94.5 |
| | | | 4 | 602 | 94.5 |
| | | | 5 | 588 | 95.9 |
| | | Change | 0 | 594 | 96.4 |
| | | | 1 | 647 | 95.2 |
| | | | 2 | 647 | 94.8 |
| | | | 3 | 636 | 93.7 |
| | | | 4 | 652 | 94.0 |
| | | | 5 | 650 | 96.3 |
| | No Flash | Repeat | 0 | 565 | 95.2 |
| | | | 1 | 595 | 96.5 |
| | | | 2 | 603 | 94.6 |
| | | | 3 | 595 | 94.0 |
| | | | 4 | 606 | 95.4 |
| | | | 5 | 591 | 96.3 |
| | | Change | 0 | 607 | 96.4 |
| | | | 1 | 645 | 95.7 |
| | | | 2 | 647 | 94.6 |
| | | | 3 | 631 | 94.4 |
| | | | 4 | 648 | 95.0 |
| | | | 5 | 643 | 95.2 |

| | Alerting | Colour | Location | RT (ms) | ACC (%) |
|---|---|---|---|---|---|
| **Experiment 4** | | | | | |
| | Flash | Repeat | 0 | 559 | 96.0 |
| | | | 1 | 596 | 95.2 |
| | | | 2 | 599 | 94.6 |
| | | | 3 | 600 | 95.4 |
| | | | 4 | 605 | 95.1 |
| | | | 5 | 599 | 96.2 |
| | | Change | 0 | 602 | 96.2 |
| | | | 1 | 655 | 95.2 |
| | | | 2 | 652 | 94.8 |
| | | | 3 | 641 | 95.6 |
| | | | 4 | 652 | 94.9 |
| | | | 5 | 653 | 96.1 |
| | No Flash | Repeat | 0 | 562 | 95.3 |
| | | | 1 | 597 | 95.6 |
| | | | 2 | 601 | 94.3 |
| | | | 3 | 596 | 94.7 |
| | | | 4 | 602 | 95.1 |
| | | | 5 | 594 | 95.5 |
| | | Change | 0 | 610 | 96.6 |
| | | | 1 | 646 | 95.7 |
| | | | 2 | 646 | 93.7 |
| | | | 3 | 638 | 94.3 |
| | | | 4 | 649 | 94.9 |
| | | | 5 | 656 | 95.5 |