Is pop-out search impaired during the period of the attentional blink?

by

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Abstract

The involvement of attention in pop-out visual search is controversial. According to some theories, efficient pop-out search is accomplished preattentively, while others claim the involvement of attention is essential. In the present work, the role of attention in performing pop-out search tasks was elucidated by manipulating the availability of attention using an attentional blink (AB) paradigm. In Chapter 2, the efficiency of pop-out search – indexed by the slope of response time (RT) functions over the number of items in the search array – was examined throughout the period of the AB. Search efficiency was found to be unaffected by the AB, although the overall level of RT was slower during the AB. These findings suggest the action of at least two separable mechanisms underlying performance in pop-out search tasks, indexed by level and efficiency of search, which are affected in different ways by the availability of attention. In Chapter 3, the role of selective attention in pop-out search was examined by measuring the onset latency of the N2pc, an event-related potential index of attentional selection. Both the RT and the N2pc measures were delayed during the AB, but the delay in N2pc was substantially shorter than that in RT. This pattern of results points to multiple sources of delay in the chain of processing events, as distinct from the single source postulated in current theories of the AB, and strongly suggests that selective attention is involved in pop-out search tasks. In Chapter 4, the relative exogenous and endogenous salience of two targets (T2, T3) presented throughout the period of the AB were manipulated in order to assess whether the perception of salience is impaired during the AB. The perception of temporal order of these targets was measured. Both exogenous and endogenous salience were found to be effective in modulating the perception of temporal order throughout the period of the AB, suggesting that the effect of salience is broadly additive with the overall AB effect. In Chapter 5, the implications of these findings for both search and the AB, are discussed and future research directions are proposed.

Keywords: visual attention; attentional blink; visual search; salience; temporal order; event-related potentials

Acknowledgements

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List of Acronyms

µV	Microvolts
AB	Attentional blink
ANOVA	Analysis of variance
cd/m^2	Candelas per square meter
CDA	Contralateral delay activity
CIE	Commission Internationale de l'Éclairage
DC	Direct current
EEG	Electroencephalography
ERP	Event-related potential
FIT	Feature Integration Theory
GS4	Guided Search 4.0
HEOG	Horizontal electrooculogram
Hz	Hertz
ISI	Inter-stimulus interval
LC	Locus coeruleus
LCD	Liquid crystal display
LCD	Liquid crystal display
ms	milliseconds
MSE	Mean square error
N2pc	N2-posterior-contralateral component
NE	Norepinephrine
Ppc	Positivity posterior contralateral
P_D	Distractor positivity

PO	Parieto-occipital
PRP	Psychological refractory period
RSVP	Rapid serial visual presentation
RT	Response time
SFU	Simon Fraser University
SOA	Stimulus onset asynchrony
SPCN	Sustained posterior contralateral negativity
T1	First target
T2	Second target
T3	Third target
TLC	Temporary Loss of Control
VEOG	Vertical electrooculogram
VSTM	Visual short term memory
VWM	Visual working memory

Chapter 1.

General Introduction[1]

1.1. Attention

As we go about our daily lives, our visual system encounters an environment that is continually changing across time and space. Even such mundane experiences as watching television, searching for a pair of socks in the laundry, or scanning the road for signs and obstacles, cause massive amounts of rapidly changing stimulation to reach the visual system. Processing all this input to the level of conscious awareness would quickly exceed the systems' processing capabilities. The brain has, therefore, evolved to process fully only a small subset of that input. The means by which this selectivity is implemented is thought to be through the mechanisms subsumed under the rubric attention.

Despite William James's (1890) statement that "Everyone knows what attention is", attention is a notoriously difficult concept to define. Some scholars have even gone so far as to say that "nobody knows what attention is" (Styles, 2006, p.1) or even that "there is no such thing as attention. There are, however, many empirical findings that can be accurately labeled attentional" (Anderson, 2011, p.1). The difficulty in defining the concept stems from the use of attention as an "umbrella" term that encompasses a wide variety of different states and processes (Chun & Wolfe, 2001; Egeth & Yantis, 1997; Pashler, 1998; Styles, 2006). Generally, however, it is agreed that attention refers to the selection and processing of mental or sensory stimuli in order to bring salient or relevant information into conscious awareness.

The limits of the brain's ability to select and process incoming stimulation have been studied in both spatial and temporal dimensions. At the outset, much of the

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research on visual attention focused on the brain's ability to select and process incoming stimulation in the spatial domain (see, e.g., Driver, 1998; Pashler, 1998, for reviews). Spatial attention in the visual modality has largely been studied with a paradigm known as visual search (see, e.g., Wolfe, 1998, for a review). In recent years, however, interest in the temporal domain has grown immensely (see, e.g., Dux & Marois, 2009; Martens & Wyble, 2010; Shapiro, Arnell, & Raymond, 1997, Shapiro & Luck, 1999; for reviews). The attentional blink (AB) phenomenon has been a key tool in the investigation of the availability of attention across time. These two classic attentional phenomena – visual search and the AB – will be discussed in the following sections (1.2 and 1.3, respectively).

1.2. Visual Search

1.2.1. The Basic Paradigm

Visual search is something that people do routinely every day. They search for a book on a shelf or for a familiar face in a crowd. In typical laboratory studies, observers search a display for a target hidden among distractors (see Figure 1.1.A. for examples). On some percentage of the trials, usually 50%, a target is present, while on the other trials, the target is absent. Participants are instructed to respond as quickly, yet as accurately, as possible to the presence or absence of a target in the search display. Typically, the primary measure of interest is the time taken to find and report the target (response time; RT), as a function of the number of items in the display (set size).

The pattern of RT over set sizes is used to estimate the efficiency of the search process. Search is said to be efficient if RT remains constant as set size is increased (i.e., slopes near 0 ms/item[2]. This is often the case when the target differs from the distractors in respect to a simple feature such as color or orientation (Figure 1.1.A, bottom panel). Under these conditions, the target is said to be salient and to "pop out" from the display. By contrast, search is said to be inefficient if RT increases as set size is increased. This is often the case when the target is defined by a combination of features,

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[2] Search slopes may actually decrease as set size increases (negative search slopes). This is thought to occur because increasing set size often involves increasing the density of items and creates stronger local contrasts (e.g., Bravo & Nakayama, 1992; Maljkovic & Nakayama, 1994). In the present work, negative search slopes are regarded as efficient.

such as a specific colour and orientation (Figure 1.1.A, top panel). This type of task is referred to as *conjunction search*.
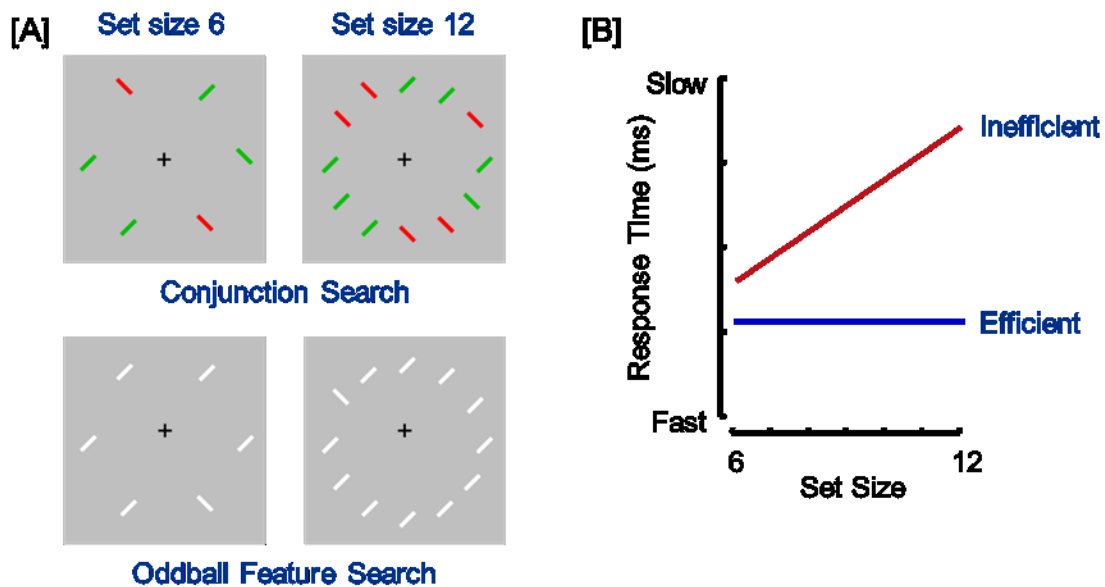
Figure 1.1. **[A] Search arrays in which the target is either defined by a specific combination of features (green and left-ward tilt, top-panel) or by a single feature (left-ward tilt, bottom-panel). [B] Hypothetical response times (RTs) for search arrays that yield efficient (flat) or inefficient (steep) search slopes.**

What Stimuli Support Efficient Search?

There is some consensus about a small number of features that usually support efficient search (Wolfe, 1998; Wolfe, 2014; Wolfe & Horowitz, 2004). These include colour, motion, orientation, and size. There is more debate over many others, like luminance onset, Vernier offset, shape, closure, curvature, and depth cues. Additionally, there is some evidence supporting the position that other learned "features", like letters and geometric shapes, can support efficient search (e.g., Egeth, Jonides, & Wall, 1972, Jonides & Gleitman, 1972; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). In the present work, in which we are interested in efficient search, we employ search displays in which the target is defined by its unique orientation (Chapter 2) or colour (Chapters 3 and 4). According to Wolfe (2014), orientation and colour are "undoubted feature dimensions", capable of guiding search "easily and effectively".

1.2.2. Theoretical Accounts of Visual Search

The distinction between efficient (Neisser, 1963) and inefficient (Atkinson, Holmgren, & Juola, 1969) search slopes was key to the development of Anne Triesman's influential Feature Integration Theory (FIT; Treisman & Gelade, 1980). The original version of FIT has a two-stage parallel-preattentive, serial-attentive architecture. In the first stage, all stimuli are decomposed into basic features, such as colour, orientation, spatial frequency, brightness, and direction of motion, which are said to be represented in separate feature maps in the brain. For example, one map might code for "blueness", while another codes for vertical orientations. These basic features are processed in parallel, without the involvement of attention (i.e., preattentively). The activity of a singleton in a feature map (e.g., a single activation in the green map produced by a green ring among an array of red rings) would cause the item possessing the unique feature to "pop-out" effortlessly. According to FIT, it is this parallel, preattentive stage which underlies efficient, pop-out search.

Inefficient search is explained in FIT by a second, serial, attentive stage. When a target is defined by a unique combination of features (e.g., a vertical green bar amongst vertical red and horizontal green bars), it will not pop-out because it will not produce unique activation in any one feature map. The preattentive stage might indicate that green, red, vertical, and horizontal features are present in the display but it cannot show which features co-occur at a single location (i.e., whether vertical co-occurs with green). FIT states that selective attention is required to integrate or "bind" features together into an object (Treisman, 1996; von der Malsburg, 1995). Otherwise, the features would be "free-floating," as evidenced by illusory conjunctions (Treisman & Schmidt, 1982).This attentive binding process was said to occur in a *master map of locations,* and to be strictly serial, occurring one item at a time. On this view, inefficient search slopes were indicative of the amount of time it took selective attention to serially inspect items in the search array, until the target was found and search could be terminated (serial self-terminating search).

Thus, according to FIT, there are two qualitatively different types of search: parallel-preattentive and serial-attentive. The efficient search slopes in feature search tasks were said to result from parallel, preattentive processing of feature information. By contrast, all types of search which yield inefficient search slopes, including conjunction

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search, were said to result from serial deployments of attention to items in the search array. Although consistent with much of the early data (e.g., Treisman, 1982; Treisman & Gelade, 1980; Treisman, Sykes, & Gelade, 1977), this idea that efficient and inefficient searches can be dichotomised into two classes has not been supported by the bulk of the current evidence.

As noted by Nakayama and Joseph (1998), the list of features capable of supporting efficient pop-out search seems to exceed biological plausibility, not only including simple features, like colour and orientation, but also complex ones, like letters, 3D cubes, and shading effects (e.g., Enns & Rensink, 1990, 1991; He & Nakayama, 1992; Kleffner & Ramachandran, 1992; Ramachandran, 1988; Wang, Cavanagh, & Green, 1994). Additionally, based on an analysis of approximately a million trials of visual search data, Wolfe (1998) demonstrated that the distribution of search slopes obtained from three different types of search tasks (feature, conjunction, and spatial-configuration) is unimodal, rather than the bi-modal or multi-modal distribution that would be expected if these different search tasks were categorically different. In particular, search for certain conjunctions of features was much more efficient than serial search would predict (e.g., Nakayama & Silverman, 1986; Theeuwes & Kooi, 1994). On the basis of these results, Wolfe (1998) concluded that "any effort to divide tasks into serial and parallel search on the basis of search slope alone will be futile" (p.34).

Instead of this dichotomous view of search, in Jeremy Wolfe's Guided Search (GS) theory one mechanism – guidance – is said to underlie *all* types of search, with the continuum of search efficiency determined by the quality of guidance. The more guidance, the more efficient the search slopes. The GS model has been updated several times (Wolfe, 1994, 2007; Wolfe, Cave, & Franzel, 1989; Wolfe & Gancarz, 1996). The latest version of the model (GS4; Wolfe, 2007) comprises two pathways, which converge at an AB bottleneck (see Figure 2.6). One is a nonselective, pathway in which parallel processing of a restricted class of stimuli, such as image statistics and some aspects of scene analysis, occur (e.g., Ariely, 2001; Chong & Treisman, 2003; Oliva & Torralba, 2001). The other is a selective pathway, characterized by an early bottleneck where selection is guided by a weighted average of signals derived from both early visual processes (bottom-up salience; Nothdurft, 2000a, b, c; Donk & van Zoest, 2008; Lamy & Zoaris, 2009), which is determined by local differences in a dimension (e.g., Itti & Koch,

2000), and by top-down reentrant processes (e.g., Di Lollo, Enns, & Rensink, 2000; Hochstein & Ahissar, 2002), based on task demands.

This guidance determines the number of items in a search array that must be attended at the selection bottleneck in order for the target to be found. Perfectly efficient search slopes (0 ms/item) are obtained when the guiding representation is strong enough to always direct attention to the target item first time, every time. Completely inefficient search slopes are obtained when no guidance is possible, such that each item in the array needs to be attended to, sequentially, one item at a time, until the target is found (serial search). Intermediate search slopes are obtained when some feature information can be used to prioritize some items for inspection over others.

Like in GS4, most recent models of visual search posit that only one mechanism underlies all the different types of search. Similar to GS4, in Müller and colleagues' Dimensional Weighting account of visual selection (Found & Müller, 1996; Müller, Reimann, & Krummenacher, 2003), target detection involves "an attentional mechanism that modifies the processing system by allocating selection weight to the various dimensions that potentially define the target" (Müller et al., 2003, p.1021). The allocation of weights to a given dimension is modulated in a top-down way, in a manner similar to top-down guidance in GS4.Other studies attribute performance to different factors including target-distractor similarity (Duncan & Humphreys, 1989), task-set configuration (Di Lollo, Kawahara, Zuvic, & Visser, 2001), and signal-to-noise ratio (e.g., signal-detection theories: Chun & Wolfe, 1996; Geisler & Chou, 1995; Hübner, 1993; Palmer, 1994, 1995; Swensson & Judy, 1981; Verghese & Nakayama, 1994).

Similar to FIT, Theeuwes' theory of stimulus-driven selection (2010, see Theeuwes, 1991, 1992 for earlier versions) claims that efficient pop-out search arises from exclusively preattentive stimulus-driven, salience-based processes. Theeuwes argues that when attention is distributed across the visual field, preattentive processing is driven exclusively by bottom-up properties of the stimuli. After this initial preattentive salience analysis of the search array, one item is selected for further processing. Theeuwes refers to this exogenous, purely stimulus-driven and automatic shift of attention as *attentional capture*. The location selected will be that with the highest local feature contrast or salience (e.g., Donk & van Zoest, 2008; Itti & Koch, 2001; Koch & Ullman, 1984; van Zoest, Donk, & Theeuwes, 2004). Once a location has been selected,

the identity of the object at that location becomes available. If that object is the target, a response can be generated; however, if that object is not the target, its location will be inhibited (Theeuwes & Godijn, 2004) and attention will shift exogenously to the location of the next most salient object. Only later in time (>150 ms after stimulus onset) will endogenous control based on expectations and task demands affect visual selection. This top-down biasing of selection is accomplished through recurrent feedback processing (e.g., Hochstein & Ahissar, 2002).

Clearly, a consensus has not been reached as to what processes underlie search performance. One notable theoretical difference is with respect to the involvement of attention in search tasks that yield efficient search slopes. At opposite ends of the spectrum are theories that posit that pop-out search tasks rely exclusively on preattentive or stimulus-driven processes (e.g., Treisman & Gelade, 1980; Theeuwes, 1991, 1992, 2010) and those that argue that top-down attention or task-set is essential for efficient search (e.g., Bacon & Egeth, 1994; Di Lollo et al., 2001; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994; Gibson & Kelsey, 1998).

The involvement of attention in pop-out visual search is the issue of primary interest to the present work. Before reviewing the evidence for the involvement of attention in pop-out search tasks (see section 1.4), I first discuss a dual-task paradigm known as the attentional blink (AB), which I have used to modulate the availability of attention to pop-out search displays in the experiments presented in Chapters 2-4.

1.3. The Attentional Blink

1.3.1. The Basic Paradigm

The human visual system is severely limited in its ability to process rapidly-changing visual stimuli. This limitation has conventionally been studied by displaying a stream of stimuli (e.g., letters, digits, images) in rapid serial visual presentation (RSVP; Lawrence, 1971; Potter & Levy, 1969; Sperling, Budiansky, Spivak & Johnson, 1971). In RSVP, stimuli are displayed rapidly (e.g., 100 ms each) and sequentially at the same location. Observers are instructed to monitor the stream for one or more targets (e.g., letters) amongst distractor items (e.g., digits). When the requirement is to report a single target, the task is quite easy, with near perfect accuracy. This finding may seem to

indicate that target processing in RSVP is complete within 100 ms (Gathercole & Broadbent, 1984; Lawrence, 1971; McLean, Broadbent, & Broadbent, 1982). However, evidence to the contrary is provided by tasks requiring the identification of an additional target from an RSVP stream.

Identification of the first of two sequential targets (T1) is typically nearly perfect, but is substantially reduced for the second (T2). The second-target deficit is known as the attentional blink (AB; Broadbent & Broadbent, 1987; Raymond, Shapiro & Arnell, 1992). The AB is most pronounced when the temporal separation between the two targets is short (200-300 ms), with performance improving progressively as the separation is increased to about 700 ms (Raymond et al., 1992). In most studies of the AB, the temporal separation between the two targets is varied in steps of about 100 ms, with each step following T1 being denoted as a separate lag. Thus, the term Lag 1 indicates that T2 was presented directly after T1, and the term Lag 3 indicates that two distractors intervened between T1 and T2. A related, although independent phenomenon (Visser, Bischof, & Di Lollo, 1999) is Lag-1 sparing: the finding that T2 performance is enhanced when presented directly after T1 (at Lag 1) relative to at subsequent lags (Lags 2 or 3; Potter, Chun, Banks, & Muckenhoupt, 1998). Thus, the temporal course of performance in an AB task generally approximates a U-shaped function of lag: accuracy of T2 identification is high at Lag 1, is most impaired at intermediate lags (e.g., Lags 2 or 3), and recovers as lag is increased up to about Lag 7 (see Figure 1.2). The magnitude of the AB effect is defined as the highest level of T2 identification (usually at the longest lag) *minus* the lowest level of T2 identification (usually at one of the shortest lags).

It is worth noting that, while typical, this U-shaped pattern of T2-identification accuracy as a function of lag is not universally observed. Lag-1 sparing is found reliably only when the two targets are presented in the same spatial location (Visser, Zuvic, Bischof, & Di Lollo, 1999). Lag-1 sparing is also typically absent when the response measure is response time (RT) to T2 (e.g., Kawahara, Zuvic, Enns, & Di Lollo, 2003, Experiment 2), or when T1 and T2 are different in two or more dimensions (Visser, Bischof, & Di Lollo, 1999). In these cases, the AB function is monotonic, with the poorest performance recorded at Lag 1.
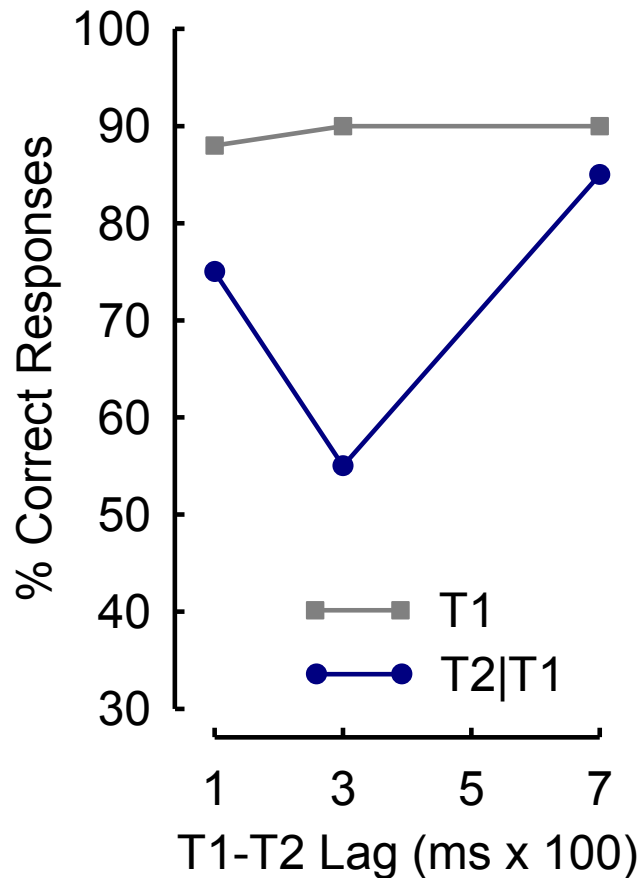
Figure 1.2.   Hypothetical pattern of results in a typical AB study.

While Lag-1 sparing is subject to these contingencies, the AB itself is a very robust effect that has been demonstrated across a variety of experimental conditions, sensory modalities, and populations (see Martens & Wyble, 2010 and Dux & Marois, 2009 for reviews). The robustness and generality of the AB effect, has made it a topic of wide interest. A simple Google Scholar search yields over 10,000 results for the term "attentional blink". The high-level of interest in this phenomenon seems to stem from the belief that the AB reflects "a very general property of perceptual awareness with broad implications for understanding how the brain perceives any task-relevant stimulus" (Martens & Wyble, 2010, p.948).

The AB Effect is Attentional, not Sensory

There is evidence to support the view that the AB effect is attentional, rather than sensory. First, identification or detection of T2 is impaired only when T1 is attended. If T1

is ignored, T2 performance is unaffected (Raymond et al., 1992). Second, event-related potential components (ERPs) obtained from electroencephalographic recordings (EEG) of a T2 presented during the AB are unimpaired for at least the first 150 ms of processing (i.e., the P1 and N1 components are unaffected; Vogel, Luck, & Shapiro, 1998). Additionally, there are a number of studies which demonstrate that "blinked" T2s (i.e., T2s presented during the AB that are not reported correctly) still activate semantic representations, as indexed by the N400 component (Luck, Vogel, & Shapiro, 1996; Pesciarelli et al., 2007; Rolke, Heil, Streb, & Hennighausen, 2001; Vogel et al., 1998), and can conceptually prime report of subsequent targets (Martens, Wolters, & van Raamsdonk, 2002; Shapiro, Driver, Ward, & Sorensen, 1997). Considered collectively, "the bulk of the evidence…does suggest that, at least for the standard AB tasks, missed stimuli are processed postperceptually" (Dux & Marois, 2009, p.1693).

The ability of the AB paradigm to produce attentional modulations while leaving sensory processing intact is important for the present work, in which we wish to distinguish between attentional and stimulus driven factors in pop-out search.

1.3.2. Theoretical Accounts of the Attentional Blink

Many theoretical accounts, both formal (i.e., computational frameworks) and qualitative (i.e., descriptive accounts), have been proposed to account for the processing limitations that are revealed by the AB. Specific accounts of the root cause of the AB can be quite diverse, including resource depletion (e.g., Ward, Duncan, & Shapiro, 1996), delayed selection (e.g., Nieuwenstein, Potter, & Theeuwes, 2009), perceptual inhibition (Raymond et al., 1992), post-perceptual suppression (e.g., Olivers & Meeter, 2008), disruption of system configuration (e.g., Di Lollo, Kawahara, Ghorashi, & Enns, 2005), interference in working memory (Shapiro, Raymond, & Arnell, 1994) and working memory consolidation (e.g., Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; Wyble, Bowman, & Nieuwenstein, 2009). The principal objective of this section is not to review all such theories comprehensively (see Dux & Marois, 2009; Martens & Wyble, 2010 for reviews), but rather to set the stage for the experiments to be reported by outlining how some major theories of the AB explain deficits in T2 processing during the period of the AB.

Theoretical accounts of the AB can be assigned to two classes broadly defined in the foregoing: T1-based and distractor-based. Theories are assigned to these classes according to the processes or events which they regard as the root cause of the AB. According to T1-based theories, T1 processing alone is sufficient to cause the AB. In distractor-based theories, on the other hand, the requirement to process T1 is not sufficient: the presence of at least one distractor following T1 is regarded as essential. For illustrative purposes, prototypical examples of the two classes of theory are presented, with occasional reference to related theories as the need arises.

T1-based Theories

The class of T1-based theories encompasses a number of individual theories that differ as to the specific cause of the AB. These include resource depletion (e.g., Ward, Duncan, & Shapiro, 1996), delayed selection (e.g., Nieuwenstein, Potter, & Theeuwes, 2009), and working memory consolidation (e.g., Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; Wyble, Bowman, & Nieuwenstein, 2009). Despite individual variations, these theories share the common tenet that the AB stems from some process or event directly associated with T1 processing.

The prototypical exemplar of AB theories is that proposed by Chun and Potter (1995). It is a two-stage model in which the first stage of processing has no capacity limitations. The features of all incoming stimuli are said to be processed in parallel in a high-capacity first stage where potential targets are rapidly identified. At this stage, identity information is volatile and vulnerable to both decay and overwriting by trailing items. Targets tentatively identified in Stage 1 are consolidated in a second stage where processing is said to be serial and capacity limited, in that only a single target can be processed at a time. The AB occurs if T2 arrives while Stage 2 is still busy processing T1. In that case, T2 is delayed in Stage 1, where it is vulnerable to decay and overwriting by subsequent items.

To account for the Lag-1 sparing phenomenon, two-stage models postulate an attentional gate set between the two stages. The gate is said to open quickly on presentation of T1 but to close sluggishly, thereby allowing the item immediately succeeding T1 (i.e., the Lag 1 item) to gain access to Stage 2, along with T1. If the Lag 1 item is T2, both targets are processed at the same time, and Lag-1 sparing ensues. Thus, according to this model, Lag-1 sparing is time-locked to the onset of T1.

Jolicœur and colleagues (Jolicœur, 1998, 1999; Jolicœur & Dell'Acqua, 1998, 1999) extended the two-stage account of Chun and Potter (1995) to form the central interference theory. This theory purports to explain, not only the AB, but a number of other tasks in which the requirement is for two targets to be identified or detected sequentially, including the psychological refractory period (PRP) task. The PRP refers to the tendency for there to be a delay in the response to the second of two sensory–motor tasks when it is executed in close temporal succession to a prior task (Pashler, 1994; Telford, 1931; Welford, 1952). The architecture of the central-interference model is very similar to that of Chun and Potter's two-stage model with an early, parallel processing stage in which sensory and perceptual encoding occurs, and a late higher-level processing stage. This model is often referred to as a bottleneck model because a processing "bottleneck" occurs in the transition from the early capacity-unlimited stage to the second, severely capacity-limited, serial encoding stage. This second stage differs from Chun and Potter's Stage 2 in that both response selection and working memory encoding are said to require this capacity-limited central processing, rather than working memory encoding alone. According to this account, an AB arises when T2 is presented before the capacity-limited stage is free from T1 processing. When this occurs, T2 is delayed prior to the bottleneck, in the first stage of processing, where it is vulnerable to masking (Jolicœur, 1999).

The *episodic simultaneous type, serial token* (eSTST) model of Wyble and colleagues (2009; see also Bowman & Wyble, 2007 for an earlier version) is one of a number of recent formal models which builds upon Chun and Potter's (1995) two-stage architecture. However, the eSTST model provides a novel theoretical justification for this architecture by proposing that the AB reflects processes involved in creating episodically distinct representations within working memory. In the first stage (the input layer), abstract identity information about each stimulus (i.e., its type; Kanwisher, 1987) is extracted. For a stimulus to be reported correctly, however, it must gain access to a later encoding stage where its identity information is bound to a token (Kanwisher, 1987) and, thereby, encoded into working memory.

For a type representation to be bound to a token, it must be enhanced by a transient attentional mechanism called the *blaster* which amplifies the strength of the stimulus's type signal. The blaster is triggered upon detection of a target and its activity lasts for approximately 200 ms, provided that no additional targets are presented during

this excitatory phase. The excitatory phase is then followed by an inhibitory phase during which the blaster is suppressed while the target undergoes a binding process that produces a corresponding token in working memory. This T1-triggered blaster suppression extends over several hundred ms and mediates the AB deficit by preventing the T2 type from being bound to a token until T1 tokenization is complete. As with the other two T1-based theories described above, this delay in T2 processing leaves it vulnerable to decay and overwriting by trailing items.

T1-triggered blaster suppression can be delayed, however, if T1 is followed directly by another target. The signal of this trailing target is amplified since it falls within the blaster's excitatory phase. This amplification causes the inhibitory phase to be overcome and Lag-1 sparing to ensue. This amplification applies to any number of targets appearing in succession, thereby extending the duration of the attentional episode, and postponing the AB. The inhibitory phase then occurs upon the end of the attentional episode.

Distractor-based Theories

As with the T1-based class of theory, the class of distractor-based theory encompasses several models, each with somewhat different accounts of the AB (e.g., Di Lollo, Kawahara, Ghorashi, & Enns, 2005; Olivers & Meeter, 2008; Olivers, van der Stigchel, & Hulleman, 2007; Raymond et al., 1992). What all these accounts have in common is the claim that the period of inattention that is the signature of the AB is triggered not by the requirement to process T1 but rather by the disruptive effect of distractors intervening between the two targets.

The original distractor-based theory is Raymond et al.'s (1992) inhibition model. Detection of a target (e.g., T1) is said to initiate an attentional episode by opening a gate to a sensory store from which items can be selected for identification. While the gate is open, any ensuing items also gain access to the sensory store. The presence in the sensory store of features from both the target and trailing distractors may cause confusion, thus interfering with target selection. When this happens, the attentional gate is locked, and a suppressive mechanism is activated to prevent further items from entering the sensory store until processing of T1 has been completed. If T2 arrives after a distractor has caused the gate to be locked, an AB occurs because the processing of

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T2 is suppressed. This model is clearly distractor based, in that if T1 is not followed by at least one distractor, the gate is not locked, and the AB does not occur.

After a period of over 10 years, during which T1-based theories dominated, renewed interest in the idea that the AB is initiated not by T1 processing in and of itself, but rather by a post-T1 distractor was spurred by the finding that no AB is observed when multiple targets (e.g., T1, T2, T3) appear in direct succession (Di Lollo et al., 2005; Kawahara, Kumada, & Di Lollo, 2006; Nieuwenstein and Potter, 2006; Olivers et al., 2007; Olivers & Meeter, 2008; Potter, Nieuwenstein, & Strohminger, 2008). The absence of an AB with successive targets has been termed the "spreading-of-the-sparing" effect (Olivers et al., 2007). This effect is in stark contrast to the finding in conventional studies in which a substantial AB is observed when just two targets are separated by a single distractor (T1, D, T2). This finding ignited a new debate about the underlying cause of the AB and promoted the development of several new models.

The temporary loss of control (TLC) model (Di Lollo et al., 2005) proposes that target selection is governed by an input filter configured endogenously to pass targets and reject distractors (see also Ghorashi, Zuvic, Visser, & Di Lollo, 2003; Kawahara et al., 2006; Visser, Bischof, & Di Lollo, 2004). A central processor is charged with both actively maintaining this input filter (by issuing repeated signals to the filter) and encoding targets into working memory. Critically, the central processor can execute only one of these operations at a time. When a target is detected, the central processor switches from issuing maintenance signals to coordinating the target's processing. In the absence of maintenance signals, the filter becomes vulnerable to exogenous disruption by stimuli (e.g., distractors) which do not match the filter's current configuration. If the item following T1 is another target, the filter will not be reconfigured since targets fit with the existing filter configuration. Targets will thus gain direct access to working memory, thereby avoiding the AB. If, however, the item following T1 is a distractor, the filter is disrupted. Any targets appearing after this disruption, while T1 is still being encoded, will not match the filter's configuration and, therefore, will be delayed until T1 processing is complete. It is only then that the input filter can be reconfigured by the central processor to once again pass targets. During this delay, T2 is vulnerable to both the decay and masking which cause the AB.

A computational model that is also distractor based is the *Boost and Bounce* (BB) model of Olivers et al. (2007; Olivers & Meeter, 2008). There are two stages of processing in the BB model. In the first stage, all items in the RSVP stream are said to undergo sensory processing during which their perceptual features, and semantic and categorical information are activated. Only a small subset of these items, however, can gain access to the second, working memory encoding stage. For an item to be encoded into working memory where it is available for report, it must be attentionally enhanced, or "boosted", by a gating mechanism. Stimuli that match the attentional set established by task instructions are boosted, whereas stimuli that do not (i.e., distractors) are inhibited, or "bounced". Detection of T1 initiates a boost of attention that vaults it into working memory. Because the boosting mechanism is sluggish, the item that immediately follows T1 is also boosted, regardless of whether it is a target or a distractor. If that item is another target (i.e., T2), it triggers another boost and is encoded into working memory along with T1. On the other hand, if that item is a distractor, a strong but transient suppression (bounce) is initiated that inhibits the processing of the next few items to prevent further distractors from being encoded into working memory. If one of those items happens to be T2, then an AB results, since the distractor-induced inhibition prevents T2 from receiving the boost it needs to undergo working-memory encoding.

Another computationally formalized distractor-based account of the AB has been proposed by Taatgen, Juvina, Schipper, Borst, and Martens (2009). In the threaded cognition model, which is built using the ACT–R framework (Anderson , Matessa, & Lebiere, 1997), the detection of a distractor during ongoing processing of T1 elicits a protective attentional mechanism that blocks processing of new stimuli until T1 processing has been completed. This account shares some similarities with T1-based theories in that the duration of the AB is tied directly to T1 processing. However, in the threaded cognition model, the AB is elicited specifically by the presence of a post-T1 distractor; hence, it should be classified as a distractor-based model.

In summary, all theories belonging to this distractor-based class, share the claim that T1 processing alone is insufficient for the occurrence of the AB. Instead, they all claim that it is the presence of distractors intervening between the two targets which is essential for the occurrence of the AB.

The finding that the AB occurs even in the absence of distractors intervening between the two targets (e.g., Lagroix, Spalek, Wyble, Jannati, & Di Lollo, 2012; Nieuwenstein, Potter, & Theeuwes, 2009) casts serious doubt on the ability of distractor-based theories to account for the root-cause of the AB. In a recent review of the AB literature, Dux and Marois (2009) concluded that the T1-based eSTST model of Wyble et al., (2009) is capable of accounting for the largest number of empirical findings. That being said, there is still much debate, over precisely which processes underlie the AB, much like with visual search. What is not disputed, however, is the ability of the AB paradigm to modulate the availability of attention.

1.4. Is Pop-Out Search Affected by the Availability of Attention?

The extent to which goal-directed (attentive) and stimulus driven (preattentive) factors control visual selection has been extensively explored using attentional capture paradigms. Attentional capture occurs when a task-irrelevant stimulus receives attentional priority (Folk & Remington, 1998; Theeuwes, 1992). There are two opposing accounts concerning the influence of goal-directed and stimulus driven factors in attentional capture: the stimulus-driven capture account (e.g., Theeuwes, 2010) and the contingent capture hypothesis (e.g., Folk, Remington, & Johnston, 1992).

According to the stimulus-driven capture account, the degree to which an object will capture one's attention is determined exclusively by its bottom-up salience, at least for the first 150 ms (e.g., Theeuwes, 2010). In other words, selection is initially determined by stimulus salience and is uninfluenced by any top-down goals adopted by the observer. Evidence consistent with this account comes from experiments in which participants search for a unique target among an array of distractors (e.g., a shape singleton). On some trials, a unique distractor that is more salient than the target (e.g., a colour singleton) is present in the display. If attention could be deployed solely in accordance with task demands, only the target would capture attention and the presence of the salient distractor would not affect performance. By contrast, if bottom-up salience determined attentional priority, then the salient distractor would first capture attention before attention could be re-deployed to the less salient target. Consistent with the stimulus-driven capture hypothesis, salient distractors have been shown to capture attention despite being completely irrelevant to the task (e.g., Theeuwes, 1991, 1992,

1994). These results are consistent with the idea that pop-out is determined by preattentively processed, bottom-up salience.

However, there is also evidence supporting the opposite perspective that only items that match the observer's top-down attentional set capture attention. This is called the *contingent capture* hypothesis (e.g., Folk, Remington, & Johnston, 1992). On this theory, capture is determined solely by the participant's goals and expectations. That is, capture is determined by the participant's top-down attentional set and not by bottom-up stimulus salience. Evidence consistent with contingent capture comes from studies showing that task-irrelevant distractors capture attention only when they share the target's defining feature, regardless of their salience. For example, Folk et al. (1992) found that when participants were searching for a colour-defined target, irrelevant colour singletons captured attention but sudden onsets did not capture attention. The opposite pattern of results occurred when participants searched for a target defined by its unique sudden onset: irrelevant sudden onsets captured attention but colour did not. These results are consistent with the idea that pop-out is influenced by attentional processes.

Proponents of the contingent capture hypothesis argue that results which appear consistent with stimulus-driven capture can be explained instead by top-down attentional set. Bacon and Egeth (1994; see also Pashler, 1988) have proposed that attentional capture can be mediated by two distinct strategies (or modes) of top-down selection: singleton detection and feature search. Which strategy is adopted at any given time is said to depend on task demands. Singleton-detection mode is said to be adopted when the target is a singleton that stands out as a discontinuity from the background (e.g., a red item in a field of green items). While in singleton-detection mode, any discontinuity – that is, any salient item – would capture attention. In contrast, feature-search mode would be adopted when a target cannot be identified on the basis of discontinuity, but on the basis of a specific feature (e.g., a diamond in an array of heterogeneous shapes). While in feature-search mode, only items that share the target-defining feature would capture attention. On this perspective, results which seem consistent with stimulus-driven capture might actually be due to the adoption of a singleton-detection attentional set (but see e.g., Theeuwes, 2010).

It has proven difficult to distinguish between stimulus-driven and contingent capture accounts of pop-out. One promising line of investigation for distinguishing

between these accounts is to examine performance in pop-out tasks under conditions in which attention or top-down control is impaired. If stimulus-driven factors alone determine performance in pop-out tasks, then performance should not be impaired when attention is pre-empted by another task. By contrast, if the availability of attention or top-down control is essential for performing pop-out search, then performance should suffer under conditions of reduced attentional availability.

The role of the availability of attention for visual search has been investigated in a number of previous studies. For example, Braun and colleagues (e.g., Braun 1993, Braun, 1994, Braun & Julesz, 1998; Braun & Sagi, 1990, 1991) performed a series of experiments in which attention was diverted away from a peripherally presented feature search array by the requirement to perform an attentionally demanding task at fixation. They found that accuracy of pop-out detection was unimpaired when the search task was performed concurrently with the other task, compared with when it was performed alone. This led the authors to conclude that "Feature-gradient tasks seem to be mediated exclusively by nonattentive mechanisms" (Braun & Sagi, 1990, p.56).

A different pattern of results was obtained by Di Lollo, Kawahara, Zuvic, and Visser (2001). They demonstrated that if a detection task which yielded efficient, flat search slopes when done singly (single task condition) had to be performed after an unrelated task (dual task condition), the search slope became inefficient. Di Lollo et al. interpreted these results as being consistent with contingent capture, and indicating that "the key factor in determining the efficiency of early visual processing lies not in the nature of the stimuli or tasks, but in whether they can be handled optimally by the current configuration of the input system" (p.489). They argued that, under dual-task conditions, the search task had to be performed using an "ill-suited configuration" (p.490) resulting in inefficient search performance. They propose that the failure of Braun and colleagues (specifically Braun & Sagi, 1990; Braun & Julesz, 1998) to find dual-task interference may have been due to their secondary task being too simple.

This issue has also been addressed by Joseph, Chun, and Nakayama (1997) who manipulated the amount of attention available to perform a pop-out search task by using an AB paradigm. They found a search array which yielded efficient search slopes when done singly and inserted it as the second target in an AB paradigm. They reasoned that if pop-out search could be performed preattentively, then it should not be

affected by the AB. Contrary to the preattentive account of pop-out search, accuracy of target detection in the pop-out task was severely impaired during the period of the AB.

Ghorashi, Smilek, and Di Lollo (2007) noted, however, that in the Joseph et al. (1997) experiment in which pop-out search was performed during the period of the AB, only a single set size was used. This did not permit an assessment of search efficiency during the period of the AB, raising the possibility that what may have been impaired by the AB was not the search process itself, but rather some processes that preceded or followed the search, such as stimulus encoding or response selection (see Sternberg, 1969; Woodman, Vogel, & Luck, 2001).

Ghorashi et al. (2007) followed up on this work by including search arrays with two different set sizes in the AB paradigm. Consistent with the findings of Joseph et al., they found that the overall level of performance in the search task was impaired during the AB. Interestingly, inconsistent with the findings of Di Lollo et al. (2001), they found search efficiency to be invariant with lag, suggesting that, the availability of attention did not affect the efficiency of pop-out search. In Chapter 2, however, I argue that the experimental conditions in this work do not allow for an unambiguous interpretation of these results.

1.5. The Present Work

The role of attention in efficient pop-out search remains controversial. Mixed results have been obtained from studies in which the availability of attention for performing pop-out search tasks was manipulated. Some results suggest that pop-out search is unaffected by the availability of attention (e.g., Braun & Sagi, 1990), while others suggest that pop-out search is dramatically affected by the availability of attention (e.g., Belopolsky, & Theeuwes, 2010; Di Lollo et al., 2001; Joseph et al., 1997), and still others show mixed results (e.g., Ghorashi et al., 2007). The experiments presented in Chapters 2 to 4 of this dissertation were designed to add to this literature, and to help resolve some of these inconsistencies, by addressing the following questions:

(1) Is the efficiency of pop-out visual search impaired during the period of the AB? (Chapter 2)

(2) Is pop-out visual search postponed during the period of the AB? (Chapter 3)

(3) Does stimulus salience modulate the perception of temporal order throughout the period of the AB? (Chapter 4)

The work reported in Chapters 2 to 4 are presented in their original published format. Brief prefaces are included for Chapters 3 and 4 to relate the purpose of these chapters to the outcomes of the experiments reported in the previous chapters. The collective implications of these studies and suggestions for future directions are discussed in Chapter 5.

Chapter 2.

Is pop-out visual search attentive or preattentive? Yes![3]

2.1. Abstract

Is the efficiency of "pop-out" visual search impaired when attention is preempted by another task? This question has been raised in earlier experiments but has not received a satisfactory answer. To constrain the availability of attention, those experiments employed an attentional blink (AB) paradigm in which report of the second of two targets (T2) is impaired when it is presented shortly after the first (T1). In those experiments, T2 was a pop-out search display that remained on view until response. The main finding was that search efficiency, as indexed by the slope of the search function, was not impaired during the period of the AB. With such long displays, however, the search could be postponed until T1 had been processed, thus allowing the task to be performed with full attention. That pitfall was avoided in the present Experiment 2.1 by presenting the search array either until response (thus allowing a postponement strategy) or very briefly (making that strategy ineffectual). Level of performance was impaired during the period of the AB, but search efficiency was unimpaired even when the display was brief. Experiment 2.2 showed that visual search is indeed postponed during the period of the AB, when the array remains on view until response. These findings reveal the action of at least two separable mechanisms, indexed by level and efficiency of pop-out search, which are affected in different ways by the availability of attention. The Guided Search 4.0 model can account for the results in both level and efficiency.

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[3] This chapter has been published as Lagroix, H.E.P., Di Lollo, V. & Spalek, T.M. (2015). Is pop-out visual search attentive or preattentive? Yes! *Journal of Experimental Psychology: Human Perception and Performance, 41*, 556-564.

2.2. Introduction

Is the efficiency of "pop-out" visual search impaired when attention is preempted by another task? This question has been raised in earlier studies (e.g., Joseph, Chun, & Nakayama, 1997; Ghorashi, Smilek, & Di Lollo, 2007), but has not received a satisfactory answer because, as we argue below, the experimental conditions employed in those studies did not allow for an unambiguous conclusion. The present work is aimed at providing an answer to the initial question while avoiding the pitfalls of the earlier work.

Visual search is something that people do routinely every day. They search for a book on a shelf or for a familiar face in a crowd. In typical laboratory studies, observers search a display for a target hidden among distractors. Estimates of the efficiency of visual search are obtained from the time taken to find and report the target—response time (RT)—as a function of the number of items in the display (set size). Search is said to be efficient if RT remains constant as set size is increased. This is often the case when the target differs from the distractors in respect to a simple attribute such as color or orientation. Under these conditions, the target is said to "pop out" from the display. Conventionally, these pop-out tasks are regarded as preattentive, which means that the stimuli do not require attention to be processed (Treisman & Gelade, 1980).

The idea that pop-out search is preattentive was questioned by Joseph et al. (1997), who reasoned that if pop-out search does not require attention, then performance in pop-out tasks should not be modulated by the availability of attention. To test this claim, they used a dual-task paradigm known as the attentional blink (AB), in which perception of the second of two rapidly sequential targets (T2) is impaired when presented within about 500 ms of the first (T1; Raymond, Shapiro, & Arnell, 1992; Enns, Visser, Kawahara, & Di Lollo, 2001). It is commonly believed that this T2 deficit occurs because attention is preempted by T1. Based on the hypothesis that pop-out search does not require attention, Joseph et al. reasoned that no AB deficit should occur if T2 was a search array in which the target popped out.

As a first step, Joseph et al. (1997) set out to find a task that met the conventional criterion for being processed preattentively, namely, a task that yielded a flat search slope. The display consisted of a circular array of either 6, 9, or 12 Gabor

patches. Observers indicated whether all patches had the same orientation or one of them was oriented orthogonally and was, therefore, an orientation oddball. Consistent with the hypothesis that the pop-out task was performed preattentively, the results revealed a flat slope of RT over set size.

This done, Joseph et al. (1997) went on to test the proposition that, if that task was truly preattentive, its performance should not be impaired during the period of the AB, while attention was unavailable or less available. To this end, Joseph et al. employed an AB paradigm in which the 12-item search array from the previous experiment was used as T2. The T2 task was to say whether all 12 Gabor patches had the same orientation or contained an orientation oddball. The T1 task was to identify a letter inserted in a stream of distractors presented in rapid serial visual presentation (RSVP).

Contrary to the preattentive hypothesis, the results revealed a substantial AB deficit: Detection of the oddball in the T2 display was severely impaired at short intertarget lags, and it improved rapidly as lag was increased. The important implication of this result is that the processing of even a simple feature such as orientation is impaired during the period of the AB, while attention is busy with T1. Joseph et al. (1997) regarded this outcome as consistent with the hypothesis that all forms of visual search – even those involving simple, primitive features – require attention.

Although, on the face of it, this was a reasonable conclusion, supported by the empirical evidence, its validity was questioned by Ghorashi et al. (2007). To quote (page 125):

> This interpretation, however, is not entirely unambiguous, because two different indices of the need for attention were used when the task was performed under single- and dual-task conditions. The slope of the search function was used in the single-task condition [i.e., in the preliminary experiment], whereas the percentage of correct responses at any given lag was used in the dual-task condition [i.e., in the AB experiment]. An implicit assumption in this approach is that the two measures—slope and accuracy of performance—index the same attentional process. However, it is commonly accepted (e.g., Sternberg, 1969) that the slope and the intercept of the search function can vary independently of one another. This was pointedly noted by Woodman, Vogel, and Luck (2001), who suggested that the slope may index the efficiency of visual search, whereas the intercept may reflect events that precede or follow the search process, such as stimulus encoding or response selection. This

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raises the possibility that the AB deficit in accuracy of second-target identification found by Joseph et al. (1997) may represent an impairment not in the search process itself but in other processing events that preceded or followed the search process.

In essence, what Ghorashi et al. (2007) were saying is that visual search is not a unitary process; rather, it has multiple processing stages that, at the very least, can be dichotomized into those processes that contribute to the slope (search), and those that contribute to the overall level of the function (encoding, response planning and execution). Furthermore, some of these processes may require attention while others do not. It may, therefore, not be appropriate to ask whether the "processing" of a pop-out display as a whole is "postponed". Rather, a more realistic question is to ask what components of the processing sequence – notably those indexed by the slope and by the level of the search function – are affected by the availability of attentional resources.

Ghorashi et al. (2007, Experiment 1A) set out to resolve this ambiguity by replicating the essential aspects of Joseph et al.'s (1997) study with the notable exception that two different set sizes (6 and 12 items) were used at each of three intertarget lags. The dependent measure was RT, which permitted the slope of the search function, as well as the level of performance, to be estimated throughout the period of the AB. The results showed that RTs became progressively faster as inter-target lag was increased – a conventional AB in level of performance. Notably, however, the slopes of the search functions were invariant with lag. On the face of it, this suggested that visual search remained efficient even when attention was depleted.

To explain the invariance of the search slope over lags, Ghorashi et al. (2007) employed the logic of the psychological refractory period (Sternberg, 1969; Pashler & Johnston, 1989) and concluded that the observers postponed the search task until the processing of T1 had been completed. During the period of postponement, the search array was said to be stored in a buffer in readiness for the search process. This means that, regardless of lag, the search task was performed outside the period of the AB and, therefore, under conditions of full attention. Clearly, this negated the purpose of the study, which was to find out whether pop-out search could be performed in the absence of attention.

Even though consistent with the results, Ghorashi et al.'s (2007) postulation of a buffer in which a representation of the search array could be stored until T1 had been

processed is not strictly necessary. This is because, in that study, the search array remained on the screen until the observer responded. This may have allowed the observers to adopt a strategy of completing the processing of T1 and then searching the array on the screen, thus performing the search task under conditions of full attention, regardless of lag. On this option, the question of whether pop-out search can be performed during the period of the AB remains unanswered.

To determine whether pop-out search can be performed efficiently when attention is absent or much reduced, a way must be found of compelling the observers to perform the search task during the period of the AB, rather than postponing it until processing of T1 has been completed. In the present work, this was done by presenting the search array for a brief period of 50 ms after which the screen was blank. Considering that it takes approximately 50 ms for the stimulus to arrive at primary visual cortex (Bullier, 2001; Lamme & Roelfsema, 2000), the search cannot be performed while the image is on the screen. Rather, it must be performed on the internal representation of the search display.

Such internal representations are commonly referred to as informational persistence, which is known to be available for periods of 150-300 ms after the offset of the inducing stimulus (Di Lollo & Dixon, 1988; Irwin & Thomas, 2008). This means that, given a 50-ms display, there is only a total of 200 to 350 ms during which a representation of the display is available to be searched. Bearing in mind that the period of the AB extends for at least 500 ms from the onset of T1, it is clear that, under these conditions, the visual search must be carried out within the period of the AB, at least when the inter-target lag is 100 ms.

2.3. Experiment 2.1

The principal objective of Experiment 2.1 was to determine whether efficient pop-out search can be performed during the period of the AB, namely, while the availability of attention is reduced. The design of the experiment comprised two main conditions, presented in separate blocks of trials: In the Brief condition, the search array was displayed for 50 ms. In the Long condition, the search array remained on the screen until the observer responded. On the reasoning outlined above, the search could be postponed until T1 had been processed in the Long condition but not in the Brief

condition. The Long condition was the same as in Experiment 1A of Ghorashi et al. (2007). Therefore, we expected to replicate their finding that the slope of the search functions remains the same at all intertarget lags, as illustrated in Figure 2.1.A . In contrast, we expected the search slope in the Brief condition to reveal any effect of the availability of attention: If pop-out search requires attention, we expected the search slope to be steeper during the period of the AB, namely, steeper at short (e.g., Lags 1 and 3) than at long (e.g., Lag 7) inter-target lags, as illustrated in Figure 2.1.B. If, on the other hand, pop-out search does not require attention, the search slope in the Brief condition should be invariant with lag, as illustrated in Figure 2.1.A.
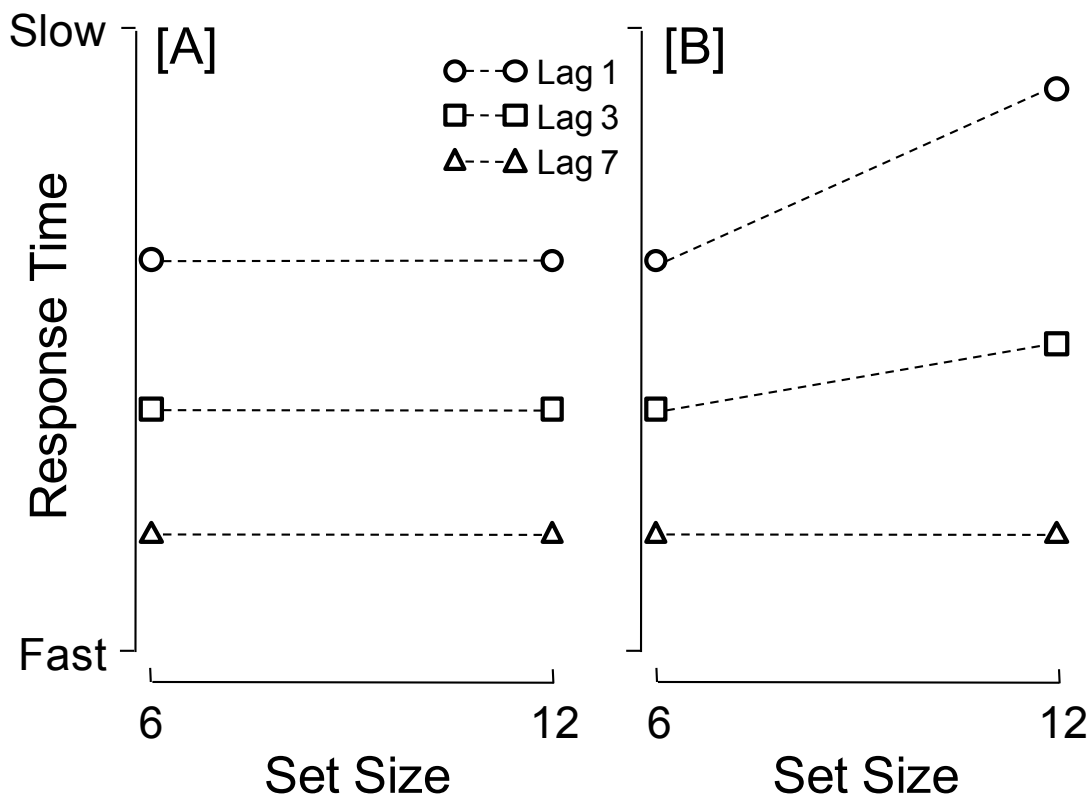
Figure 2.1. **Hypothetical response times for the T2 search array at each set size, separately for each lag. (A) Slopes of the search functions, drawn on the hypothesis that search is efficient (flat slope) and invariant with lag either because the search is preattentive or because it is postponed until T1 has been processed; (B) slopes of the search functions, drawn on the hypothesis that pop-out search requires attention and, therefore, becomes inefficient (steep slope) while the availability of attention is reduced during the period of the AB (Lags 1 and 3).**

2.3.1. Methods

Participants

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

Apparatus and Stimuli

Stimuli were displayed on a BENQ XL2410T color monitor, refreshed at a rate of 120 Hz. The background was gray (7.0 cd/m2, as measured by a Minolta CS 100 photometer) and contained a black fixation cross (0.5 cd/m2) that subtended 0.5° of visual angle at the center of the screen. The stimuli consisted of black uppercase letters (0.5 cd/m2), a white uppercase letter (90.0 cd/m2), and a set of white line segments (90.0 cd/m2), each subtending 0.5°× 0.2° of visual angle, spaced regularly around a circle of 2.5° radius, centered at fixation. The line segments were tilted 45° either to the left or to the right. All letters subtended 0.6° of visual angle vertically.

Procedure

All displays were viewed from a distance of approximately 57 cm. At the beginning of each trial, the fixation cross was presented in the center 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 RSVP consisted of a sequence of black-letter distractors presented in the center of the screen. The letters were drawn randomly without replacement from the English alphabet (excepting Q). Each letter was displayed for 50 ms and was separated from the next letter by an inter-stimulus interval of 50 ms, during which the display was blank. Thus, the stimulus onset asynchrony (SOA) between successive items in the RSVP stream was 100 ms.

T1 was a white letter inserted in the RSVP stream, and it was preceded by between 5 and 10 black-letter distractors at random. T2 was a search display comprising either 6 or 12 tilted line segments, as described above. On half the trials, all line segments had the same orientation; on the remaining half of the trials, the search display contained one line segment in the opposite orientation (an orientation oddball). The tilt of the line segments was determined randomly on each trial. There were three

intertarget lags. At Lags 1, 3, and 7, the onset of T1 preceded that of T2 by 100, 300, and 700 ms, respectively. The RSVP stream continued to be displayed during the intertarget interval and for the first 50 ms of T2. In the Brief condition, T2 remained on the screen for 50 ms after which the screen was blank. In the Long condition, T2 remained on the screen for 5 s or until the observer made a response, whichever came first. An example of the display sequence is presented in Figure 2.2.
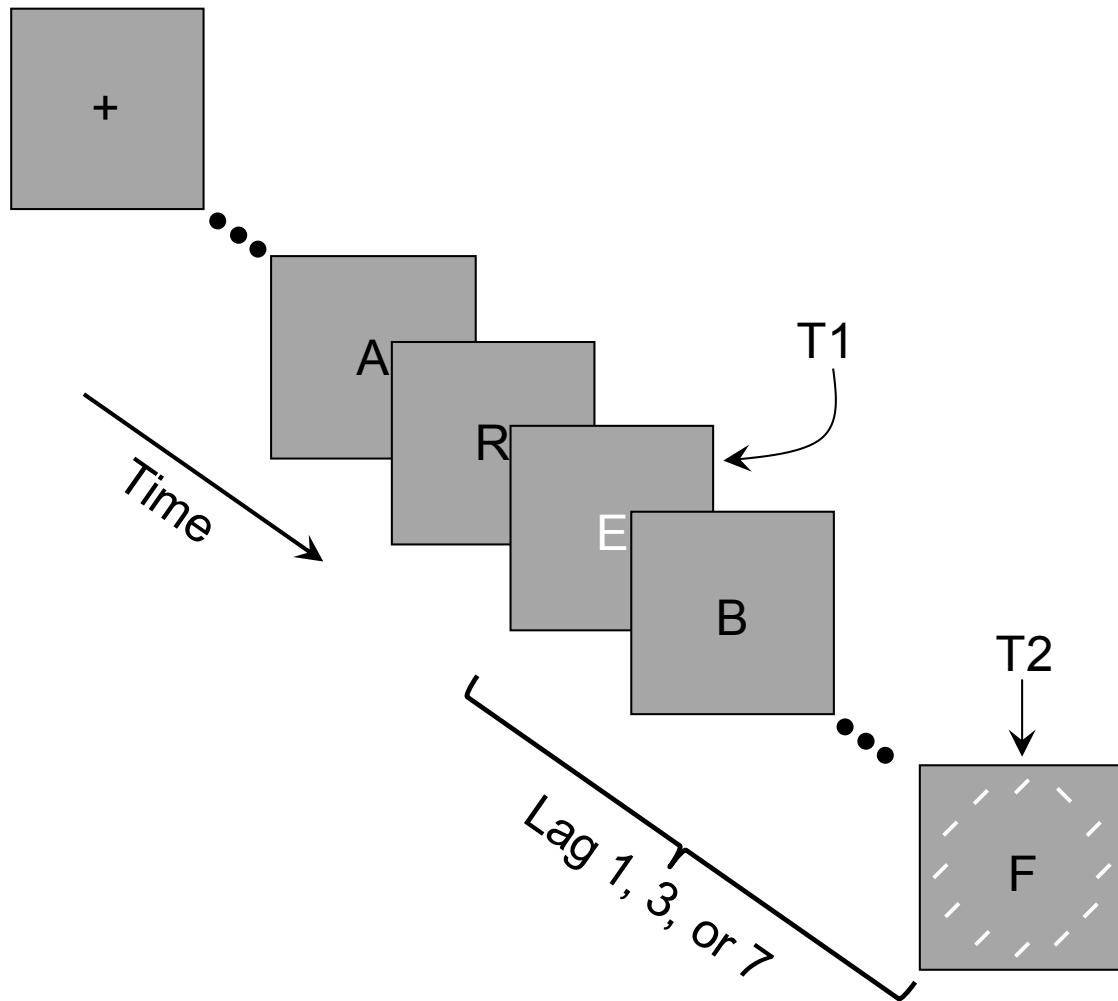
Figure 2.2.   Schematic representation of the display sequence. The number of elements in the search array was either 6 or 12 (illustrated).

Observers performed two tasks on each trial. They were instructed to first respond as quickly, yet as accurately, as possible to the presence or absence of the oddball in the T2 search display. Responses were made by pressing the left-arrow key (present) or the down-arrow key (absent) on the keyboard. Upon making a response to

the T2 stimulus, a prompt was displayed on the screen asking observers to identify the T1 letter, at their leisure, by pressing the corresponding key on the keyboard.

Each observer performed four blocks of 150 trials each, one block for each combination of display duration (brief, long) and set size (6,12). The order of the blocks was counterbalanced across observers with the constraint that the two blocks for the same display duration always occurred in succession. This was done to facilitate the establishment and maintenance of a specific strategy, notably, a postponement strategy in the Long condition. This resulted in eight different orders which were administered across observers (3 observers per order). Within each block, intertarget lag and presence or absence of the oddball were randomly intermixed, with the constraint that there were an equal number of trials per condition. Each block was preceded by 6 practice trials.

2.3.2. Results and Discussion

In this and all subsequent experiments, estimates of RTs to T2 were based only on those trials on which both targets were identified correctly. The procedure of including in the analysis only trials on which T1 is identified correctly is commonly used in AB studies on the grounds that on trials in which T1 fails to be identified, the source of the error is unknown, thus its effect on T2 processing cannot be evaluated.

The mean percentage of correct responses, averaged over set size, oddball presence, display duration, and lag, was 91.4% for T1 and 96.3% for T2. Median RTs to T2 were calculated for each observer at each of the three lags in the two set-size conditions, separately for oddball-present and oddball-absent trials, and for display duration. These data, averaged over observers, are presented in Table 3.1. An ANOVA performed on the RT data summarized in Table 3.1 comprised four within-subject factors: Set Size (6, 12), Oddball Presence (present, absent), Lag (1, 3, 7), and Display Duration (brief, long). The analysis revealed a significant effect of Lag, $F(2, 46) = 132.98$, $p < .001$, MSE = 11,045.67, confirming that a substantial AB deficit in level of performance occurred with RT as the dependent measure. The Oddball Presence × Set Size interaction was significant, $F(1, 23) = 10.62$, $p = .003$, MSE = 7,643.02, confirming that the search slopes were more negative on oddball-present trials. The Display Duration × Lag interaction was also significant, $F(2, 46) = 4.17$, $p = .022$, MSE =

6,211.50. No other effects, notably the Set Size × Lag interaction and the Display Duration × Set Size × Lag interaction, reached significance (Fs < 1)[4].

Table 2.1.   Median Response Times (RTs) and Percentages of Correct Responses

| | | | Set Size = 6 | | | | | | Set Size = 12 | | | | | |
| | | | Target Absent | | | Target Present | | | Target Absent | | | Target Present | | |
Exp.	Disp. Dur.	Measure	Lag 1	Lag 3	Lag 7	Lag 1	Lag 3	Lag 7	Lag 1	Lag 3	Lag 7	Lag 1	Lag 3	Lag 7
1	Long	% T1	91.3	93.7	95.3	88.0	94.8	93.8	88.3	93.2	93.5	88.5	92.8	92.8
		% T2|T1	96.9	98.5	97.2	97.1	96.9	98.5	97.6	97.2	97.1	96.8	98.3	98.9
		RT (ms)	919	793	748	974	840	768	952	811	734	910	794	736
	Brief	% T1	86.8	91.2	90.8	88.0	91.3	92.2	88.2	91.5	93.2	88.8	93.0	93.3
		% T2|T1	90.9	95.6	96.1	92.9	95.9	96.1	91.2	94.0	96.3	97.2	96.2	97.4
		RT (ms)	966	835	799	959	858	814	960	821	798	903	812	789
2	Long	% T1	88.0	91.5	89.7	84.7	92.0	89.2	87.3	89.8	88.8	86.0	90.3	88.2
		% T2|T1	95.0	96.7	97.1	95.5	97.1	97.1	94.9	96.7	93.6	94.5	93.6	94.2
		RT (ms)	888	797	769	916	814	781	861	796	746	863	770	723
	Brief	% T1	87.3	91.0	91.7	84.7	90.3	91.2	88.3	89.3	91.7	85.2	90.3	89.2
		% T2|T1	90.2	96.4	94.8	93.8	95.5	95.8	88.3	94.0	94.5	95.8	95.8	97.1
		RT (ms)	1008	832	801	976	865	836	953	806	784	936	805	771

Exp = Experiment; Disp. Dur. = Display Duration (T2 search array); ms = milliseconds

In conjunction with the nonsignificant interaction between set size and lag, the absence of a significant 3-way interaction among display duration, set size, and lag is especially important to the main objective of the present study. It indicates that the efficiency of pop-out search – as indexed by the slope of the search function – is invariant with lag not only when the search array remains on view until response (thus

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[4] We followed up this analysis with a second ANOVA that included as a factor the order in which the blocks of trials were performed. Predictably, the results paralleled those of the first ANOVA. The main effect of Order was not significant, F (7, 16) = 1.61, p = .203. Three interactions effects involving order were significant: Display Duration × Order, F (7, 16) = 6.01, p = .001, MSE = 29,034.83; Set Size × Order, F (7, 16) = 5.50, p = .002, MSE = 18,855.99; and Display Duration × Set Size × Order, F (7, 16) = 4.85, p = .004, MSE = 6,640.97. The finding that order of presentation affected performance in the Display Duration and in the Set Size conditions is not surprising because those were the factors that were blocked. On inspection, it is clear that those interactions represent the effect of practice at the experimental task. For example, RTs were consistently faster for the condition that was done second. This practice effect was stronger in the Brief than in the Long condition, which is not surprising because observers could master the task more rapidly when the search array was available indefinitely than when it was displayed for only 50 ms. Given that the main objective of the present work was to study how the efficiency of visual search is affected by the availability of attention as manipulated by inter-target lag, it is important to note that none of the interactions involving Order and Lag was significant (all ps > .26). This means that the effects of Lag revealed in the first ANOVA were invariant with the order in which the blocks of trials were sequenced.

allowing the search to be postponed), but also when the postponement option is disallowed by presenting the search array only briefly, thus forcing the search to be performed during the period of the AB. These effects are illustrated in Figures 2.3.A and 2.3.B for the long and the brief display durations, respectively. Following the practice of Ghorashi et al. (2007), and in view of the non-significant Oddball Presence × Set Size × Lag interaction effect, the data were collapsed across the Oddball Present and Oddball Absent trials in all the figures.

Figure 2.3. **Response times for the T2 search array at each set size, separately for each lag in Experiment 2.1. (A) Long display duration; (B) Brief display duration. Error bars represent standard error of the mean.**

The compelling conclusion from this pattern of results is that pop-out visual search can be performed efficiently even while attention is unavailable – or is less available –during the period of the AB. This is consistent with Treisman and Gelade's (1980) claim that pop-out search is performed preattentively, but is inconsistent with Joseph et al.'s conclusions that pop-out search requires attention. Further theoretical implications of these findings are considered in the General Discussion.
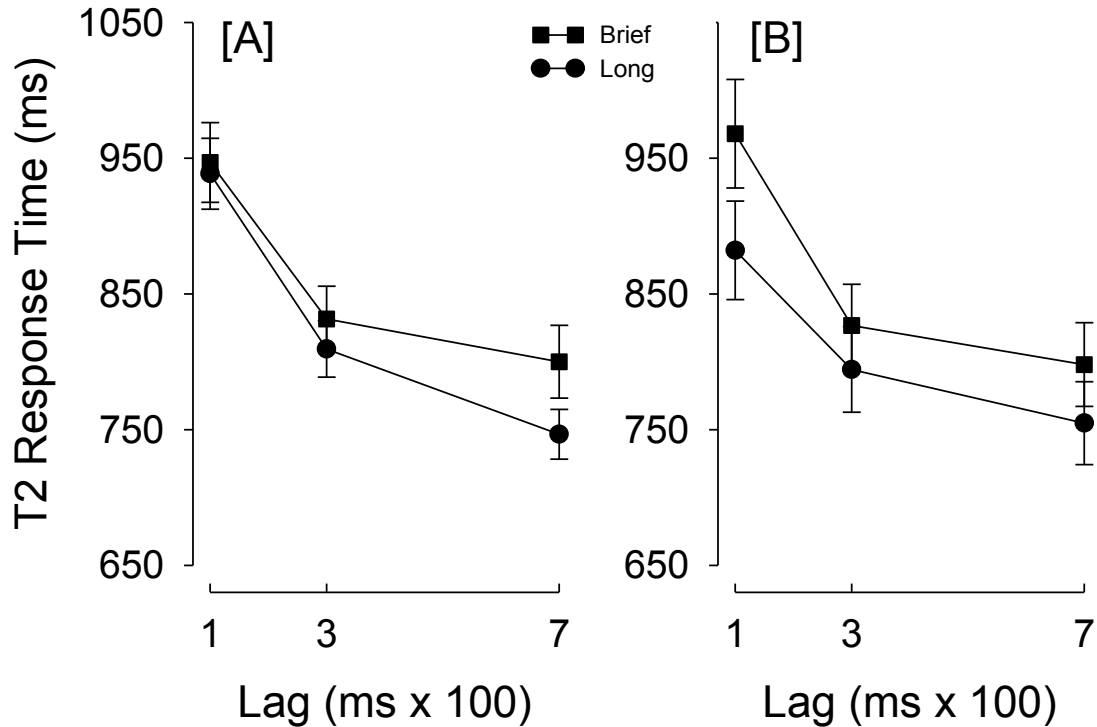
Figure 2.4. **Response times for the T2 search array at each lag, separately for the Long and the Brief display conditions. (A) Experiment 2.1; (B) Experiment 2.2. Error bars represent standard error of the mean.**

Evidence that observers adopted a postponement strategy in the Long condition, as suggested by Ghorashi et al. (2007), is provided by the significant Display Duration × Lag interaction, illustrated in Figure 2.4.A. At Lag 7, RTs were faster in the Long than in the Brief condition [$t(23) = 2.56$, $p < .02$], suggesting that the task was easier with long displays. It could be, for example, that long displays had greater contrast because of Bloch's law, or that the search could be performed without recourse to a fading memory representation. Whatever the cause, we refer to the shorter RTs as a "baseline advantage" for the Long condition. That advantage, however, was much reduced at the shorter lags (Lags 1 and 3; $ps > .29$) causing the two functions to diverge over lags (Figure 2.4.A). That divergence can be explained on the principle that postponing the search at the shorter lags would be advantageous in the Long condition but not in the Brief condition.

No postponement is ever advantageous in the Brief condition because, if the search were postponed until T1 processing was completed, there would be no array available to be searched. Hence, in that condition, the only sensible strategy is to begin

the search as soon as possible upon array onset. In contrast, in the Long condition, a postponement strategy would enable the display to be searched with full attention. Such a strategy, however, comes at a cost in RT. The cost would be maximal at the shorter lags where longer postponements are required for T1 processing to be completed, and least – or non-existent – at Lag 7, at which T1 processing should be completed. Consequently, RTs in the Long condition will be slowed down more at the shorter lags than at Lag 7. These temporal contingencies offer an account for the divergent functions seen in Figure 2.4.A.

We tested these conjectures in Experiment 2.2 by presenting the Long and the Brief display conditions randomly intermixed across trials instead of blocked, as in the present experiment. We reasoned that a postponement strategy would be inappropriate when the duration of the display is unpredictable from trial to trial. Namely, if the search were postponed on a Brief trial, there would be no array available to be searched at the end of the postponement period. Thus, when display duration is unpredictable from trial to trial, the optimal strategy is to perform the search immediately upon the onset of the search array in both the Long and the Brief conditions.

These considerations lead to the following two predictions. First, RTs in the Brief condition should be the same as the corresponding RTs in Experiment 2.1. This is because the same immediate-search strategy should be adopted in the Brief condition, regardless of whether the conditions are blocked or mixed. Second, the Long-condition advantage seen at Lag 7 in Experiment 2.1 (Figure 2.4.A) should be in evidence also at the shorter lags. This is because the mixed presentation forces the adoption of a single (immediate-search) strategy. Therefore, RTs should be the same in the Long and in the Brief condition, except for the fact that the search task is easier when the display is long, resulting in faster RTs in the Long condition at all lags.

2.4. Experiment 2.2

2.4.1. Methods

Participants

Twenty-four undergraduate students drawn from the same population as Experiment 2.1 participated for course credit or payment.

Apparatus, Stimuli, and Procedures

These were the same as in Experiment 2.1, with the exception that the Long and the Brief conditions were mixed across trials instead of being blocked.

2.4.2. Results and Discussion

The mean percentage of correct responses, averaged over set size, oddball presence, display duration, and lag, was 89.0% for T1 and 94.9% for T2. Median RTs to T2 were calculated for each observer at each of the three lags in the two set-size conditions, separately for oddball-present and oddball-absent trials, and for Long and Brief display durations. These data, averaged over observers, are presented in Table 3.1.

An ANOVA performed on the RT data summarized in Table 3.1 comprised four within-subject factors: Set Size (6, 12), Oddball Presence (present, absent), Lag (1, 3, 7), and Display Duration (brief, long). The analysis revealed a significant effect of Lag, $F(2, 46) = 77.11$, $p < .001$, MSE = 15,118.94, confirming the presence of a substantial AB deficit. The effect of Display Duration was also significant, $F(1, 23) = 25.99$, $p < .001$, $MSE = 16,095.68$, confirming the evidence obtained at Lag 7 in Experiment 2.1 that the task was easier with long displays. The Display Duration × Lag interaction, illustrated in Figure 2.4.B, was also significant, $F(2, 46) = 6.91$, $p = .002$, MSE = 5,567.65. No other effects, notably the Set Size × Lag interaction and the Display Duration × Set Size × Lag interaction, reached significance (Fs < 1), indicating that the efficiency of visual search was not impaired during the period of the AB.
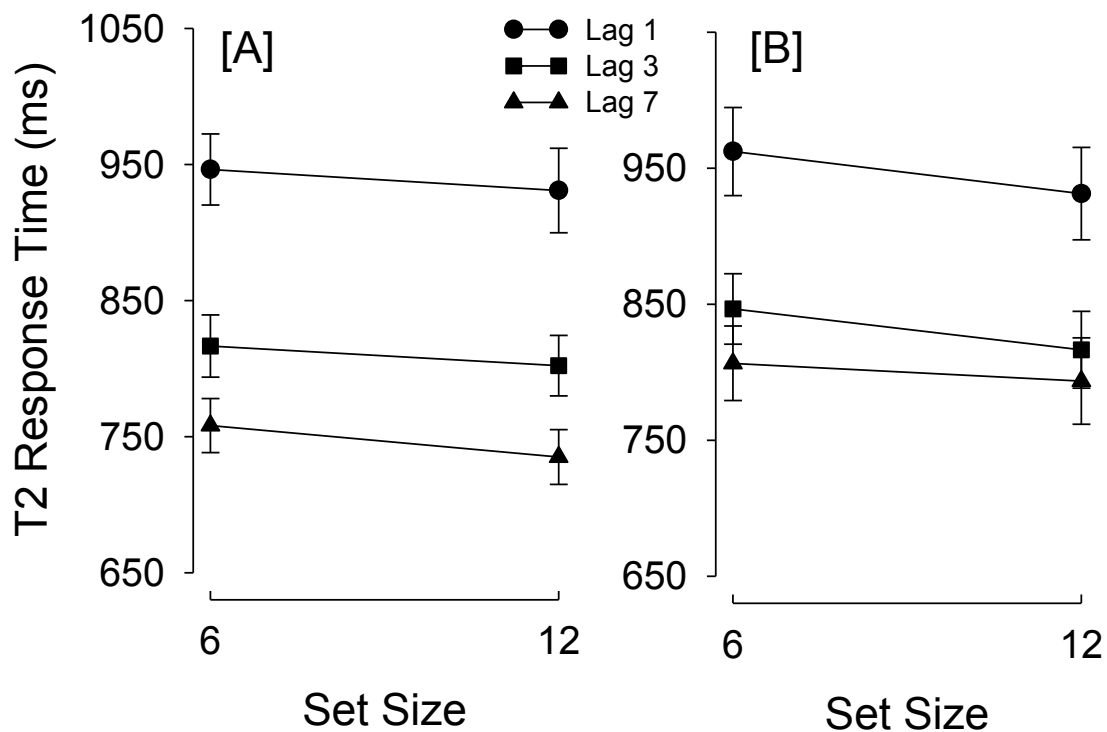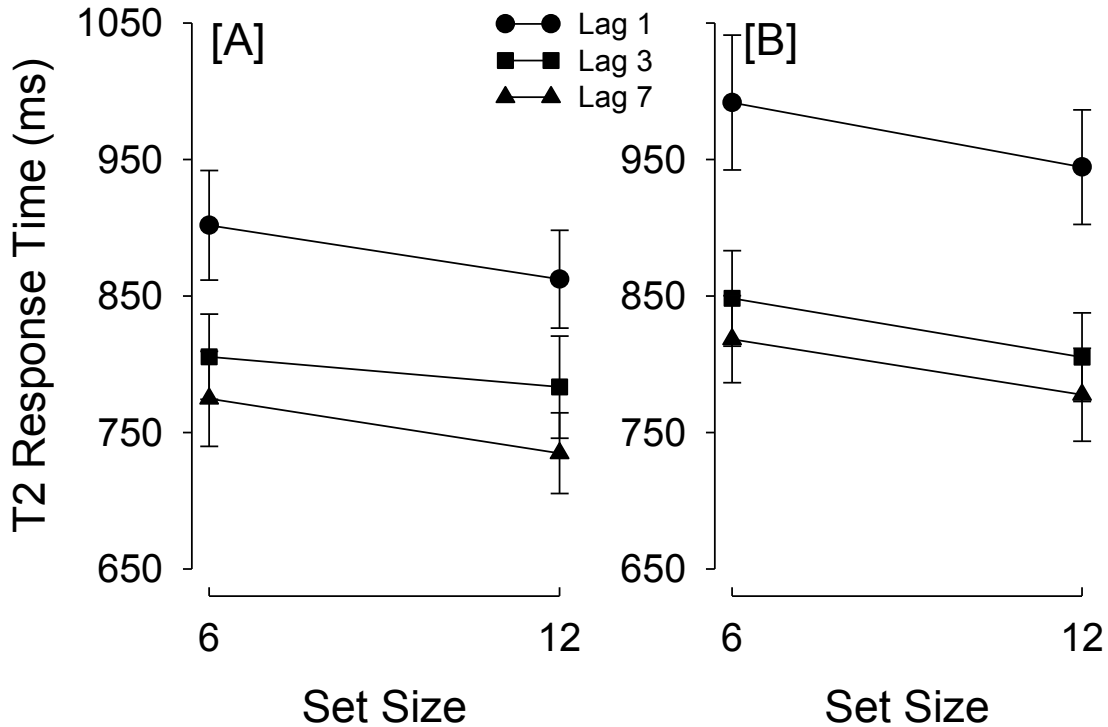
Figure 2.5. Response times for the T2 search array at each set size, separately for each lag in Experiment 2.2. (A) Long display duration; (B) Brief display duration. Error bars represent standard error of the mean.

In most details, the results of Experiment 2.2 (Figures 2.5.A and 2.5.B) matched those of Experiment 2.1 (Figures 2.3.A and 2.3.B), strongly suggesting that the experimental outcomes were invariant with whether exposure duration was blocked or mixed across trials. A mixed-factors ANOVA performed on the results of Experiments 2.1 and 2.2 revealed only one effect involving Experiment: the Display Duration × Lag × Experiment interaction effect, discussed below, $F(2, 92) = 8.64$, $p < .001$, MSE = 5,889.57.

The principal objective of the present experiment was to test the hypothesis that visual search was postponed at the shorter lags in the Long condition when the duration of the display was blocked, as in Experiment 2.1, but not when it was mixed, as in Experiment 2.2. Two specific predictions were made. First, that RTs in the Brief condition should not differ between Experiment 2.1 (Figure 2.4.A) and Experiment 2.2 (Figure 2.4.B) because an "immediate" search strategy was hypothesized to be adopted in the Brief condition in both experiments. This prediction was confirmed by the outcome

of a mixed-factors ANOVA with one within-subject factor (Lag: 1, 3, 7) and one between-subjects factor (Experiment: 2.1, 2.2). The analysis revealed a significant effect of Lag, $F(2, 92) = 135.39$, $p < .001$, MSE = 2,510.64. Neither the effect of Experiment nor the interaction effect was significant (Fs < 1). This pattern of results is consistent with the hypothesis that the same immediate-search strategy was adopted in the Brief condition in both experiments.

The second prediction was that the Long-condition advantage seen at Lag 7 in Experiment 2.1 (Figure 2.4.A) should be in evidence at every lag in Experiment 2.2 (Figure 2.4.B). This prediction was confirmed in Experiment 2.2 by planned pairwise comparisons between the Long and the Brief conditions which revealed that the two conditions differed significantly at each lag: Lag 1, $t(23) = 5.23$, $p < .001$; Lag 3, $t(23) = 3.30$, $p = .003$; Lag 7, $t(23) = 3.06$, $p = .006$.

Interpretation of the significant Display Duration × Lag × Experiment interaction effect, reported above, involves a comparison between the results in Figures 2.4.A and 2.4.B. In testing the first prediction, the Brief condition was shown not to differ between experiments. This suggests that the interaction arose from a difference between experiments in the Long condition across lags. This was confirmed in a subsidiary mixed-factors ANOVA on the results of the Long condition. The analysis, which comprised one within-subject factor (Lag: 1, 3, 7) and one between-subjects factor (Experiment: 2.1, 2.2), revealed a significant effect of Lag, $F(2, 92) = 143.13$, $p < .001$, MSE = 2,232.33, and a significant interaction effect, $F(2, 92) = 5.77$, $p = .004$, MSE = 2,232.33. The effect of Experiment was not significant ($F < 1$). The result of this analysis is consistent with the idea that, during the period of the AB, visual search was postponed in the Long condition when display duration was blocked but not when it was mixed[5].

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[5] This finding seems to imply that performance of an ostensibly preattentive (pop-out) task can come under task-set control. At issue here is whether a process can be both preattentive and under cognitive control (i.e., be non-obligatory). A similar issue has been raised when examining the relationship between automatic and controlled processes, namely, whether an automatic process can come under cognitive control (e.g., Risko & Besner, 2008). A discussion of these issues, however, is beyond the scope of the present work. We thank an anonymous reviewer for pointing out the importance of these considerations.

2.5. General Discussion

The principal question examined in the present work was whether pop-out visual search requires attention. In practice, we asked whether the efficiency of pop-out visual search is impaired during the period of the AB, while attention is unavailable, or less available. Earlier work (Ghorashi et al., 2007) found that search efficiency was not impaired during the AB, suggesting that pop-out search can be performed without focused attention. That conclusion is questionable, however, on the grounds that in Ghorashi et al.'s study the search array remained on view until response, thus allowing observers to postpone the search until T1 had been processed. The task could then be performed by searching the array on the screen, thus performing the search with full attention. In the present Experiment 2.1, the search array was displayed either until response (thus allowing a postponement strategy) or very briefly (thus rendering that strategy ineffectual). The results showed that search efficiency – as indexed by the slope of the search function – was invariant with exposure duration and lag, consistent with the idea that pop-out search does not require attention. Experiment 2.2 provided evidence that visual search is indeed postponed when the array remains on view until response.

2.5.1. Does pop-out visual search require attention?

Considered collectively, the present results are consistent with the claim that efficient pop-out search – as indexed by the slope of the search function – can be performed without attention. On the face of it, this claim is inconsistent with the results of Joseph et al. (1997) who found that detection of a pop-out T2 was impaired during the period of the AB. As noted above, however, what was impaired during the AB in Joseph et al.'s study was the level of performance; no estimate of efficiency could be obtained in that study because the number of items in the search array was not manipulated. As noted in the foregoing, the level of performance is said to reflect events that precede or follow the search process, such as stimulus encoding or response selection, whereas the slope of the search function is regarded as indexing the efficiency of the search itself.

The present conclusion that pop-out search is not affected by the availability of attention also seems at odds with the phenomenon known as priming of pop-out or intertrial priming (Malijkovic & Nakayama,1994) which refers to enhanced identification

of a target on trial N when the same target-defining attribute appeared on trial N-1 (repeat trials), relative to when the attribute changed between trials (change trials).

Intertrial priming has been interpreted as evidence for top-down attentional guidance in pop-out visual search (Wolfe, Butcher, Lee, & Hyle, 2003; Lamy, Carmel, Egeth, & Leber, 2006). An analogous conclusion was reached by Soto, Humphreys, and Heinke (2006) who found that pop-out search can be influenced by the contents of working memory. As was the case for the study of Joseph et al. (1997), however, the effects revealed in the Soto et al. study were on the level of performance, not on search efficiency because the number of elements in the search array was not varied, thereby preventing an assessment of the search slope.

On the other hand, the number of items in the search array was manipulated in the studies of Wolfe et al. (2003) and of Lamy et al. (2006) who found evidence that intertrial priming affects the level of performance – but not the efficiency – of visual search. Consistent with the present results, these studies found faster RTs on repeat trials than on change trials (i.e., a difference in the level of performance). The search functions, however, were parallel, indicating that the efficiency of visual search was not affected by intertrial priming.

2.5.2. Theoretical Accounts

Extant theories of visual search generally agree that pop-out search can be performed without the involvement of focal attention. The prime example is Treisman and Gelade's (1980) claim that pop-out search is performed preattentively. A similar claim has been made by Theeuwes (2010) who regards pop-out as arising from exclusively stimulus-driven, salience-based processes, independent of attention.
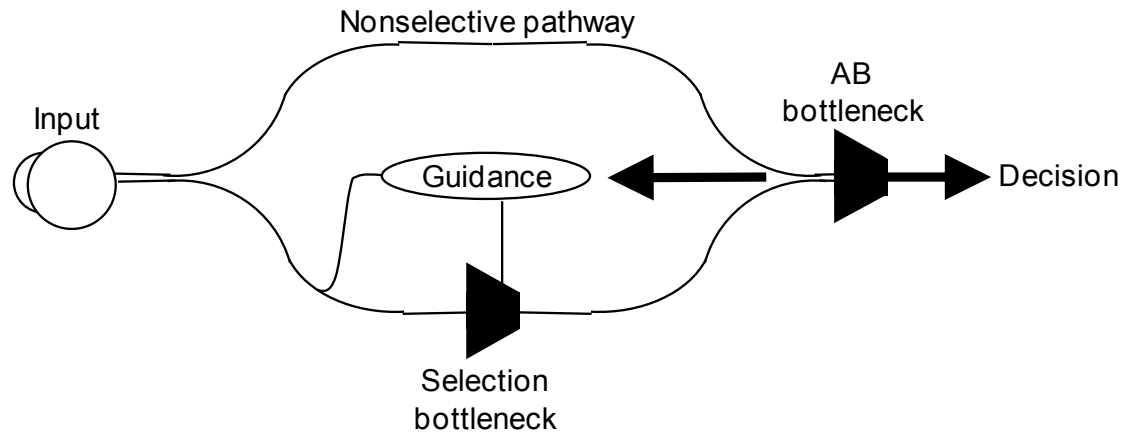
Figure 2.6. **Architecture of the Guided Search 4.0 model. Redrawn from Figure 8.2 of Wolfe (2007).**

Wolfe's latest version of the Guided Search model (GS4; Wolfe, 2007) is especially relevant because it offers an account of the finding that the AB affects the level and the efficiency of performance in different ways (Ghorashi et al., 2007; the present work). The architecture of GS4 is illustrated in Figure 2.6, redrawn from Figure 8.2 of Wolfe (2007).

The model comprises two pathways. One is a selective pathway, characterized by an early bottleneck where selection is guided both by signals derived from early visual processes and by top-down reentrant processes (e.g., Di Lollo, Enns, & Rensink, 2000; Hochstein & Ahissar, 2002). The other is a nonselective, pathway which is not limited by the selective bottleneck and is tuned to a restricted class of stimuli such image statistics and some aspects of scene analysis. Embedded in the selective pathway is a selective processing bottleneck, which occurs early in the sequence of processing. The two pathways converge at the AB bottleneck, which occurs later, at higher processing levels.

GS4 can account naturally for the joint findings that (a) the efficiency of pop-out search is not impaired during the period of the AB, and that (b) the level of performance suffers during that period (Ghorashi et al., 2007; the present work). On the GS4 account, search efficiency is not affected during the period of the AB because the search is performed in the selection bottleneck, which precedes the AB bottleneck (Figure 2.6). As such, search efficiency may be influenced by factors inherent in the selection bottleneck, but not by factors inherent in the AB bottleneck. Once the selection bottleneck has been

cleared, target consolidation depends on the state of the AB bottleneck which, in turn, depends on inter-target lag. At long lags, the bottleneck is clear, and the target is consolidated without delay. When lag is short, however, consolidation is delayed in the bottleneck, and the target is vulnerable to decay and to overwriting by trailing items during the period of delay. An AB deficit in level of performance then follows.

2.5.3. Concluding remarks

As commonly posed in the experimental literature, the question of whether pop-out visual search is preattentive is predicated on the implicit assumption that pop-out search is a single, unitary process (e.g., Joseph et al., 1997). The outcome of the present – and of related – research suggests that this is not the case. Namely, pop-out search yields at least two indices of performance: level and efficiency. The important thing is that the two indices are affected in different ways by the availability of attention, suggesting the action of at least two separable underlying mechanisms: those underlying level of performance require attention; those underlying efficiency do not. From this perspective, the question of whether pop-out visual search can be performed without the involvement of focal attention is ill-posed. What needs to be specified is what aspect of the search task is influenced by attention. The present work is a step in that direction.

Chapter 3.

Visual search is postponed during the period of the AB: an event-related potential study[6]

3.1. Preface

On the findings of Chapter 2, it appears as though pop-out search is performed just as efficiently within the period of the AB as outside the period of the AB. Clearly, however some aspects of processing related to the pop-out search task were substantially delayed during the period of the AB since RTs to T2 differed dramatically across lags. The question then becomes what aspects of processing are delayed? In the present chapter, we look at attentional selection of the oddball target, as indexed by the N2pc event-related potential (ERP) component.

3.2. Abstract

In the phenomenon known as the attentional blink (AB), perception of the second of two rapidly sequential targets (T2) is impaired when presented shortly after the first (T1). Studies in which T2 consisted of a pop-out search array provided evidence suggesting that visual search is postponed during the AB. In the present work, we used behavioural and electrophysiological measures to test this postponement hypothesis. The behavioural measure was response time (RT) to T2; the electrophysiological measure was the onset latency of an event-related-potential index of attentional selection, known as the N2pc. Consistent with the postponement hypothesis, both measures were delayed during the AB. The delay in N2pc was substantially shorter than that in RT, pointing to multiple sources of delay in the chain of processing events, as distinct from the single source postulated in current theories of the AB. Finally, the finding that the N2pc was delayed during the AB strongly suggests that attention is involved in the processing of pop-out search arrays.

3.3. Introduction

The human visual system is severely limited in its ability to process rapidly-changing visual stimuli. This limitation has been studied with a phenomenon called the attentional blink (AB) in which perception of the second of two targets is impaired when the temporal lag between them is shorter than about 500 ms (Raymond, Shapiro, & Arnell, 1992). Accounts of the AB differ, but it is generally agreed that the second-target deficit occurs because of attentional constraints arising from the requirement to process the first target.

In the conventional AB paradigm, two targets (T1 and T2; e.g., two letters) are inserted in a stream of distractors (e.g., digits) displayed in rapid serial visual presentation (RSVP). In a variant of this paradigm, T1 is still embedded in an RSVP stream of distractors, but T2 involves a visual search in which the target is an oddball (e.g., a tilted line segment) presented within an array of distractors (e.g., line segments oriented orthogonally to the target). Observers report the presence/absence of the oddball. There are two indices of performance in such search tasks: (a) response time (RT) and/or accuracy, and (b) efficiency, as indexed by the slope of the function relating RT to the number of items in the search array (set size): the shallower the slope, the more efficient the search. Both RT and accuracy have been found to be impaired during the period of the AB (Ghorashi, Smilek, & Di Lollo, 2007; Joseph, Chun, & Nakayama, 1997). Surprisingly, however, Ghorashi et al. found search efficiency to be entirely unaffected. Namely, the slope of the search function was invariant with inter-target lag. This slope invariance led Ghorashi et al. to conclude that visual search is postponed during the period of the AB until processing of T1has been completed. During the postponement, the internal representation of the search array (T2) was said to be stored in a preattentive buffer. Once attentional resources were again available for T2, the search task could be performed efficiently as though there had been no delay.

3.3.1. Electrophysiological Investigations of Visual Search During the AB

The main objective of the present study was to examine this postponement hypothesis by means of electrophysiological recordings. We used a component of the event-related potential (ERP), the N2pc, which is a negative deflection in the ERP

waveform that occurs 200-300 ms post stimulus over posterior scalp regions contralateral to the target. The latency of the N2pc is thought to index the time at which selective attention is deployed to the target (e.g., Eimer, Kiss, & Cheung, 2010; Dowdall, Luczak, & Tata, 2012). We reasoned that if the search task – and hence the deployment of attention to T2 – is postponed during the period of the AB, the postponement should be reflected in the latency of the N2pc.

The relationship between T2-processing and the N2pc has been examined in a number of earlier studies (Akyürek, Leszczyński, & Schubö, 2010; Brisson & Jolicœur, 2007; Corriveau et al., 2012; Dell'Acqua, Sessa, Jolicœur, & Robitaille, 2006; Jolicœur, Sessa, Dell'Acqua, & Robitaille, 2006a, b; Lien, Croswaite, & Ruthruff, 2011; Robitaille, Jolicœur, Dell'Acqua, & Sessa, 2007; Verleger, Śmigasiewicz, Michael, & Niedeggen, 2012). The main consideration for the present work, however, is that the paradigms employed in these studies are not directly comparable to the oddball paradigm employed by Ghorashi et al. (2007). Notably, with the two exceptions noted below, the T2 stimulus employed in these studies was not a conventional search array as used by Ghorashi et al. Mainly for this reason, those earlier studies cannot be used to assess Ghorashi et al.'s hypothesis that visual search is postponed during the period of the AB.

The two exceptions are the studies of Corriveau et al. (2012), and Lien et al. (2011) in which the T2 stimulus consisted of a search array. The usefulness of these two studies for evaluating Ghorashi et al.'s (2007) search-postponement hypothesis, however, is constrained by procedural differences. Corriveau et al. employed a compound search task in which the target location within the search array was demarcated by a salient place-holder that contained the target to be identified. A similar compound-search task was used by Lien et al. An important consideration is that, in both those studies, the process of identifying the target consisted of two steps: target localization and target identification, thus involving a task switch within the T2 task (Enns, Visser, Kawahara, & Di Lollo, 2001). What renders the outcomes of these two studies unsuitable for evaluating Ghorashi et al.'s search-postponement hypothesis is that the N2pc could not be attributed unambiguously to the process of searching for the target location (e.g., Eimer et al., 2010; Dowdall et al., 2012) or to the process of identifying the target itself (e.g., Hickey, Di Lollo, & McDonald, 2009). In addition, both Corriveau et al. and Lien et al. employed a paradigm known as Psychological Refractory Period (PRP) in which observers made speeded responses to both targets. Executing a

speeded response to the first target could affect T2 processing – and hence the N2pc triggered by T2 – in ways that might prejudice comparison with the Ghorashi et al. experiments.

Equivalence of the pop-out and the compound search paradigms with respect to the latency and amplitude of the N2pc cannot merely be assumed. There are no studies in which the N2pc obtained with a pop-out search task was compared directly with the N2pc obtained with a compound search task. Furthermore, even if it were the case that the pop-out and the compound search paradigms triggered equivalent N2pc components, it is still not known whether the results obtained with the two paradigms are affected in different ways during the period of the AB. Similar considerations apply for the N2pc obtained with the PRP and the AB paradigms. A case has been made for the AB to be regarded as a special case of the PRP (Jolicœur, 1999). But, there are no studies in which the N2pc component obtained with the two paradigms have been compared directly. Thus, it cannot be assumed that the latency and amplitude of the N2pc – which in the present study is used as an index of search postponement – is invariant with the experimental paradigm.

3.3.2. The Present Study

In the present study, the T1 task was to indicate the parity of a digit presented in an RSVP stream of letter distractors. The T2 task was to detect the presence/absence of a colour oddball in an otherwise uniformly-coloured search array. On the twin assumptions that (a) the latency of the N2pc is an index of attentional deployment, and (b) the search task is postponed during the period of the AB, the latency of the N2pc to the T2 oddball should be longer when the inter-target lag is short than when it is long. This is because at short lags the T2 search task is performed during the period of the AB and is, therefore, postponed until T1-processing has been completed, with a consequent delay in the N2pc elicited by T2. In contrast, at the longer lags, the T2 search task is performed outside the period of the AB, namely, after T1 has been processed. In this case, no delay in T2 processing – and hence no delay in the N2pc – is to be expected. The present study was a test of this expectation.

3.4. Methods

3.4.1. Participants

Seventeen paid observers took part in this experiment. Three were excluded because of excessive eye movements and blinks, resulting in less than 50% of trials after artefact correction. The remaining fourteen participants (six female, two left handed, aged 26-46 years; mean age 32.5 years) all had self-reported normal or corrected-to-normal vision.

3.4.2. Apparatus and Stimuli

Stimuli were presented on a 22" Samsung wide SyncMaster 2233 LCD monitor with a refresh rate of 100 Hz. The stimuli consisted of digits and uppercase letters presented in gray (CIE color coordinates .324/.348) and red and green coloured rings (red .09/.338; green .262/.558). All stimuli were equiluminant at 12 cd/m2 and were presented against a black background. The alphanumeric characters subtended 0.8 degrees of visual angle vertically. Each ring subtended 0.8 × 0.6 degrees of visual angle and were arranged in a search array consisting of six rings positioned at equidistant points along the circumference of an imaginary circle of 6.8 degrees radius, centered at fixation. The rings were all lateralized relative to the vertical midline, corresponding to the 1, 3, 5, 7, 9, and 11 o'clock positions on a clock face. Four custom response-buttons were positioned on the desk such that button-press responses could be made with the index and middle fingers of both hands.

3.4.3. Procedure

An example of the display sequence is presented in Figure 3.1. All displays were viewed from a distance of one meter. At the beginning of each trial, a fixation cross was presented in the center of the screen for 400 ms followed by a blank screen for 200-600 ms prior to the appearance of the first item in an RSVP stream. The RSVP consisted of a sequence of grey-letter distractors presented in the center of the screen. The letters were drawn randomly without replacement from the English alphabet (except I, O, and Q). Each letter was displayed for 50 ms and was separated from the next letter by an

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inter-stimulus interval of 50 ms, during which the display was blank. Thus, the stimulus-onset asynchrony (SOA) between successive items in the RSVP stream was 100 ms.
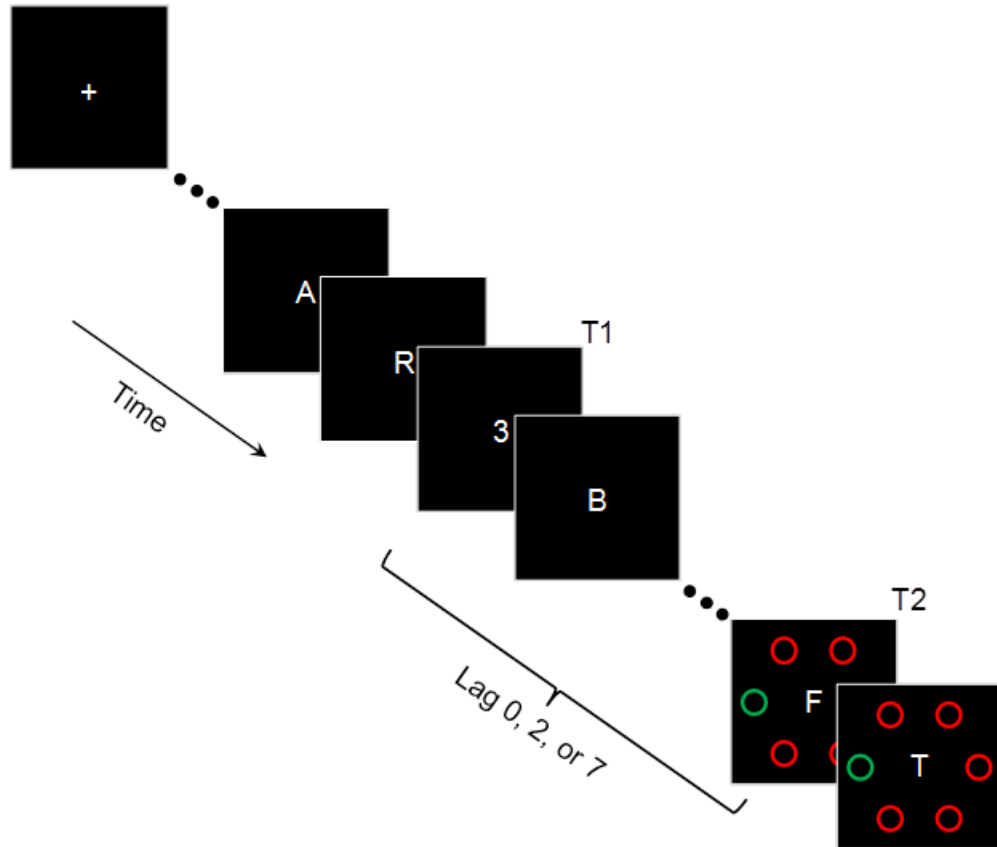
Figure 3.1. **Schematic diagram of the display sequence. The first target (T1) was a digit, the parity of which had to be reported. The second target (T2) was a search array of six coloured rings. The rings were either all of the same color (red or green) or contained one colour-oddball (one red ring amongst five green rings, or one green ring amongst five red rings). There were three inter-target lags: At Lag 0, the onset of T2 was simultaneous with that of T1. At Lags 2 and 7, the onset of T1 preceded that of T2 by 200 ms and 700 ms, respectively.**

The first target (T1) was a digit (2-9, inclusive) inserted in the RSVP stream, and it was preceded by between 5 and 8 letter distractors at random. The second target (T2) was a search display, presented for 150 ms, comprising six colored rings. On one third of the trials, all rings were the same color (all red or all green); on the remaining two thirds of the trials, the search display contained one colour-oddball (one red ring amongst five green rings, or one green ring amongst five red rings). There were three

intertarget lags. At Lag 0, the onset of T2 was simultaneous with that of T1. At Lags 2 and 7, the onset of T1 preceded that of T2 by 200 ms and 700 ms, respectively. The RSVP stream continued to be displayed during both the intertarget interval and the 150 ms duration of the search display, such that two RSVP items appeared while the search display was on view. After the search display had been presented for 150 ms, the screen went blank.

Participants performed two tasks on each trial. They were instructed to first respond as quickly as possible to the presence or absence of the oddball in the T2 search display. Responses were made using the index or middle finger of the assigned hand for an oddball-present or oddball-absent response, respectively. Upon making a response to the T2 stimulus, a prompt was displayed on the screen asking participants to identify the parity of T1 (i.e., whether the digit was even or odd) at their leisure. With the hand not used for the T2 task, participants responded with either the index or middle finger for odd or even, respectively. An even/odd response was used as the T1 task because it permitted the observers to position their fingers on the appropriate response buttons. The alternative of using a digit-identification T1 task may have introduced muscle- and eye-movement artifacts caused by searching for appropriate button on the keyboard. The hands used for the T1 and T2 tasks were counterbalanced across participants. After the two responses were made, the next trial was initiated automatically.

Each participant performed fifteen blocks of 54 trials, each counterbalanced for presence or absence of the T2 oddball, side of the T2 oddball (left or right visual field), colour of the rings in the search array, and inter-target lag. One practice block preceded the experimental blocks. Feedback on performance (T1, T2, and overall accuracy) was provided after each block.

3.4.4. EEG Recording and Data Analysis

The continuous EEG was DC-recorded at 23 electrode sites at standard positions of the extended 10/20 system (Fpz, Fz, F3, F4, F7, F8, FC5, FC6, Cz, C3, C4, T7, T8, CP5, CP6, Pz, P3, P4, P7, P8, PO7, PO8, Oz) and sampled at a rate of 500 Hz. The EEG was digitally low-pass filtered at 40 Hz, and no other filters were applied offline. All electrodes were referenced online to the left earlobe, and were re-referenced

offline to the average of both earlobes. The EEG was epoched into segments of 600 ms, ranging from 100 ms before to 500 ms after T2 onset. The segmented EEG was baseline corrected with respect to the 100-ms pre-stimulus time window. Trials contaminated with artifacts (HEOG exceeding +/- 30 µV; VEOG at Fpz exceeding +/- 60 µV; activity on all other electrodes exceeding +/- 80 µV), or with incorrect or missing responses to one or both targets were excluded from all analyses. The artefact rejection led to an exclusion of 2.7% of all trials in the Lag 0 condition, of 3.5% of all trials in the Lag 2 condition, and of 3.2% of all trials in the Lag 7 condition. In addition, oddball-absent trials were excluded from all analyses because the ERP component of interest (N2pc) can be observed only on trials on which there is a lateralized target, such as an oddball. EEG was averaged for all combinations of T1-T2 Lag (0, 2, 7) and laterality (electrode PO7/8 ipsilateral or contralateral to the location of the T2 oddball).

N2pc components to oddballs in the T2 visual search array were quantified on the basis of mean amplitudes obtained in a 240-320 ms time window after T2 onset at lateral posterior electrodes PO7 and PO8 at which the amplitude of the N2pc was maximal. Jack-knifed N2pc onset latencies were determined on the basis of grand-averaged difference waveforms, obtained by subtracting ipsi- from contralateral ERPs at PO7/8. The jackknifing procedure estimates onset latencies from grand averages that are computed from subsamples of participants where one participant is successively excluded from the original sample (Miller, Patterson, & Ulrich, 1998). N2pc onset latencies at each lag were defined as the point in time at which the N2pc difference wave exceeded an absolute voltage threshold value of -0.4 µV. This value was chosen because it was half of the maximum amplitude of the N2pc component. N2pc onset latencies at each lag were examined in a within-subjects analysis of variance (ANOVA) and paired-samples t-tests. F- and t-values were corrected according to the formula described by Ulrich and Miller (2001) and Miller et al. (1998) and are labelled as F_c and t_c.

3.5. Results

3.5.1. Behavioural Performance

The mean percentages of correct T1 and T2 responses, as well as average median RTs to T2, are presented in Table 2.1. Assessment of behavioral performance

was based only on trials in which an oddball was present. This was done to facilitate comparison with the ERP results which can be assessed only when a lateralized stimulus (the oddball) is present.

Table 3.1. **Mean Median Response Times (RTs) and Percentages of Correct Responses (standard error in parentheses)**

Measure	Target Absent			Target Present		
	Lag 0	Lag 2	Lag 7	Lag 0	Lag 2	Lag 7
% correct T1	93.4 (1.3)	93.4 (1.2)	93.4 (0.8)	94.7 (1.5)	93.8 (1.1)	93.5 (1.0)
% correct T2|T1	96.8 (1.3)	98.1 (0.8)	99.6 (0.2)	98.9 (0.3)	99.3 (0.3)	99.4 (0.2)
Median RT (ms)	958 (61)	812 (54)	708 (60)	981 (56)	761 (47)	668 (47)

The grand average of correct T1 responses (standard error in parentheses) was 93.6% (0.9). A one-way within-subjects ANOVA performed on the T1 data yielded no significant effect of Lag ($F < 1$). Estimates of second-target identification were based only on those trials on which the parity of T1 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 T2 processing cannot be evaluated. The grand average of correct T2 responses was 99.0% (0.3). A one-way within-subjects ANOVA performed on the T2 data yielded no significant effect of Lag, $F(2, 26) = 1.50$, $p = .243$. The absence of an effect of Lag on either T1 or T2 accuracy was to be expected given that the experiment was designed to optimize response accuracy so as to retain the largest possible number of trials. To this end, we presented no mask after T2 and, to avoid the inherent response ceiling, we used RT instead of accuracy as the dependent measure. The idea that RT and accuracy are both legitimate indices of the AB deficit has been proposed by Ruthruff and Pashler (2001). That idea has been supported by other research showing that much the same pattern of AB results is obtained with T2 search tasks very similar to ours when the dependent measure is accuracy (e.g., Joseph et al., 1997) as when it is RT (e.g., Ghorashi et al., 2007).

Estimates of RT were based only on those trials on which correct responses were made to both targets. Trials with anticipatory RTs (shorter than 200 ms) and very slow responses (RTs longer than 2500 ms) were excluded from analysis (less than 1% of all correct trials). Median RTs to the T2 stimulus were calculated for each observer at each of the three lags. A one-way within-subjects ANOVA performed on the RT data yielded a significant effect of Lag, $F(2, 26) = 100.79$, $p < .001$, $\eta^2 = .886$. A comparison

of RT at Lags 0 and 7, $t(13) = 10.87$, $p < .001$, and at Lags 2 and 7, $t(13) = 8.35$, $p <$ .001, confirmed that a substantial AB deficit occurred with RT as the dependent measure. RT was slower at Lag 0 than at Lag 2, revealing no evidence of sparing at Lag 0, $t(13) = 9.16$, $p < .001$.

3.5.2. ERP Results

Figure 3.2 (top panel) shows ERPs obtained for the three Lags (0, 2, 7) at electrodes PO7/8 contralateral and ipsilateral to the side of the T2-colour-oddball. The N2pc components can be seen more clearly in the difference waveforms obtained by subtracting ipsilateral from contralateral ERPs (Figure 3.2, bottom panel). The presence of N2pc components was confirmed with an ANOVA performed on the mean amplitudes measured at electrodes PO7/8 in the 240-320 ms post T2-onset time window (Figure 3.2, top panel). The range of 240-320 ms was selected because the N2pc components were maximal within that time window[7]. A 2 (Laterality: contralateral, ipsilateral) × 3 (Lag: 0, 2, 7) within-subjects ANOVA revealed a significant effect of Laterality, $F(1, 13) = 12.43$, $p = .004$, $\eta^2 = .489$, demonstrating that the N2pc was reliably present. The main effect of Lag was also significant, $F(2, 26) = 36.95$, $p < .001$, $\eta^2 = .740$, revealing that the mean amplitudes of the ERP components differed across Lag. On the face of it, this effect of Lag reflects the finding illustrated in Figure 3.2 (top panel) that the overall level of the ERP component in the N2pc time range is lower at Lag 2 than at either Lags 0 or 7. This effect is examined in the Appendix. Importantly, however, the Laterality × Lag interaction was not significant, $F = 1.77$, indicating that the differences in mean amplitude between the contra- and ipsilateral ERP components – that is, the mean amplitude of the N2pc components – did not differ across lags.

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[7] Following a suggestion by an anonymous reviewer, we extended the analysis window to 600 ms post-stimulus to explore for evidence of a sustained posterior contralateral negativity (SPCN). The extended analysis revealed no evidence of an SPCN component. This is to be expected, as previous studies have found that unlike the N2pc, the SPCN is elicited only in tasks in which response selection requires the in-depth processing and identification of target stimuli. No SPCN is triggered in tasks that simply require the detection of pop-out targets (Mazza, Turatto, Umiltà, & Eimer, 2007).
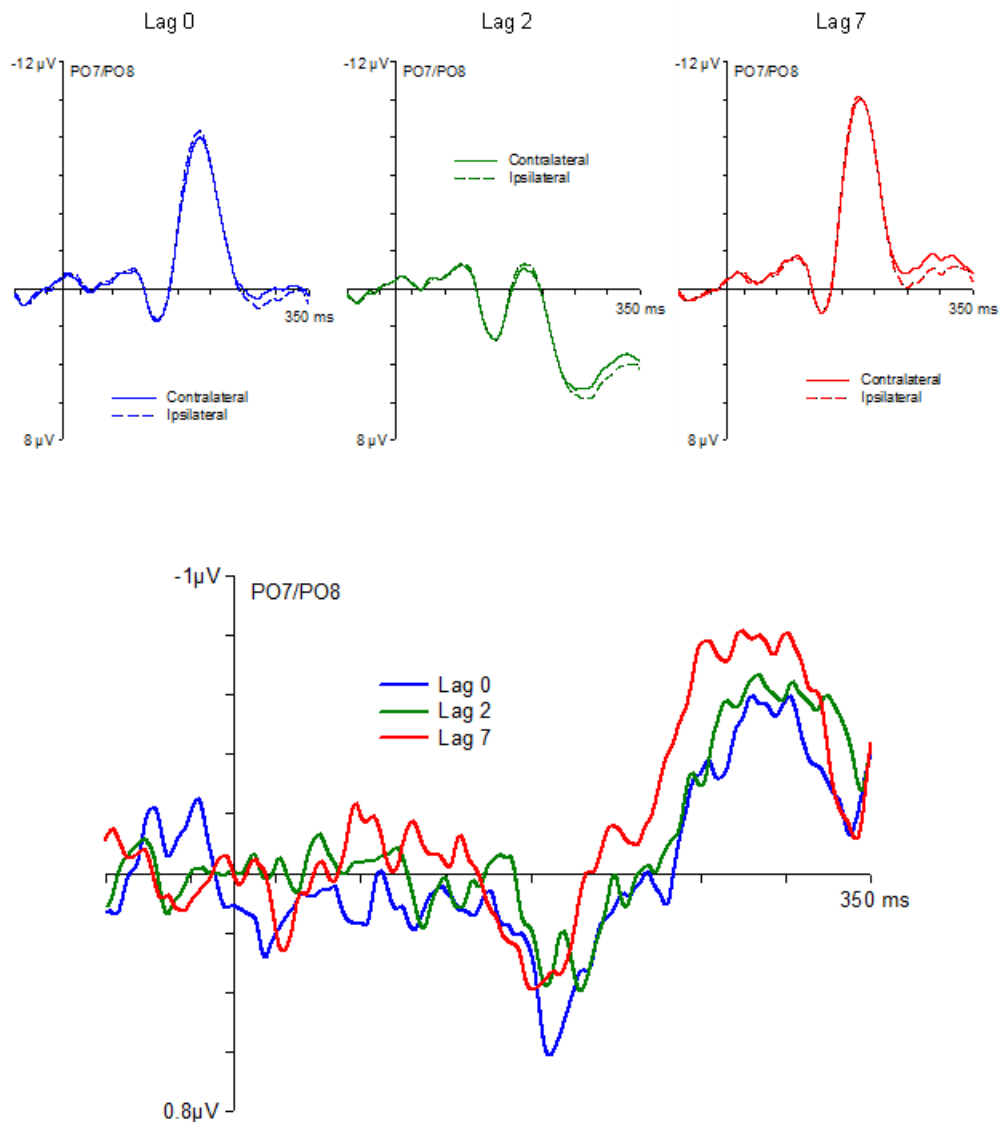
Figure 3.2.   Grand-averaged ERPs measured at posterior electrodes PO7/8 contralateral and ipsilateral to the location of the T2-oddball at Lags 0, 2, and 7. The bottom panel shows difference waveforms obtained by subtracting ipsilateral from contralateral ERPs in response to the T2-oddball at each Lag.

Of principal interest to the present work was the relative onset latencies of the N2pc components at each Lag. On Ghorashi et al.'s (2007) hypothesis that visual search is postponed during the period of the AB, we expected the latency of the N2pc to the T2 oddball to be longer when the inter-target lag was short than when it was long. A one-way within-subjects ANOVA performed on the N2pc onset latencies yielded a significant

effect of Lag, F_c (2, 26) = 4.00, p = .031, η^2 = .235. Consistent with the postponement hypothesis, paired-samples t-tests confirmed that the N2pc to the T2-oddball emerged sooner at Lag 7 than at either Lags 0 [232 ms vs. 268 ms; t_c(13) = 2.32, p = .037] or Lag 2 [232 ms vs. 256 ms; t_c(13) = 3.13, p = .008], revealing an AB in N2pc onset latency. The onset latencies of the N2pc components at Lags 0 and 2 did not differ significantly from one another [268 ms vs. 256 ms; t_c(13) = .08, p = .438][8].

3.6. Discussion

In the present work, we examined Ghorashi et al.'s (2007) claim that visual search for T2 is postponed during the period of the AB. To this end, we used the N2pc as an index of the time at which attention is deployed to the location of T2 in a search array. On the twin premises that (a) the deployment of attention is postponed during the period of the AB, and (b) that the N2pc indexes the time at which attention is deployed to the target, we expected the latency of the N2pc to be longer when the inter-target lag was short than when it was long. The results confirmed that expectation.

Qualitatively, this result is consistent with Ghorashi et al.'s (2007) proposal that visual search is postponed during the period of the AB (i.e., until processing of T1 has been completed). Quantitatively, however, the proposition that the N2pc provides a realistic estimate of that postponement is more problematic. This is because the estimate based on the RT measure (about 300 ms) is considerably longer than the corresponding estimate based on the N2pc measure (about 30 ms). Substantial discrepancies between RT and N2pc-latency differences have been found in several studies (e.g., Corriveau et al., 2012; Lorenzo-Lopez, Amenedo, & Cadaveira, 2008; Wiegand, Finke, Müller, & Töllner, 2013). Other studies, however, have found a close correspondence between the two measures (e.g., Fortier-Gauthier, Dell'Acqua, &

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[8] An additional analysis comparing the size of the N2pc at electrode sites PO7/PO8 and P7/P8 showed that the N2pc was reliably larger at electrodes PO7/PO8 [F(1, 13) = 7.98, p =.014, η2 = .380]. However, a replication of the N2pc amplitude and onset latency analyses at electrode sites P7/P8 mirrored the results found at sites PO7/PO8. The ANOVA on mean amplitudes in the 240-320 ms post-stimulus time window revealed main effects of Laterality, F(1, 13) = 8.87, p = .011, η2 = .406, and Lag, F(2, 26) = 54.34, p < .001, η2 = .807. The Laterality × Lag interaction was not significant, F = 1.44. The ANOVA on N2pc onset latencies at an absolute voltage threshold value of -0.4 µV uncovered a main effect of Lag, Fc (2, 26) = 14.15, p < .001, η2 = .521. N2pc components to the T2-oddball emerged statistically at the same time at Lag 0 and Lag 2 [275 ms vs. 282 ms; tc (13) = .09, p =.392], but emerged sooner at Lag 7 relative to Lag 0 [243 ms vs. 275 ms; tc (13) = 3.65, p =.003] or Lag 2 [243 ms vs. 282 ms; tc (13) = 5.53, p < .001].

Jolicœur, 2013; Luck et al., 2006; Töllner, Zehetleitner, Gramann, & Müller, 2011). The reasons for the different outcomes are unclear and remain to be investigated.

Before relinquishing the discussion of the difference between RT and N2pc latencies, we need to consider the option that such a difference might have arisen from the different ways in which the two values were calculated. The onset latency of the N2pc reflects the shortest latency at which the N2pc was elicited across trials at any given lag. In contrast, the mean RT reflects the average latency in processing the search array across trials at any given lag. As an extreme example of how the mean RT measure is obtained, consider a bimodal distribution with 600-ms latency on half of the trials and 300-ms latency on the other half. By combining these two distributions, the average latency in RT would be 450 ms. In the case of the N2pc, the distribution of latencies would have a temporal smearing effect on the average amplitude (which would be correspondingly reduced as the variability increased) but would have little or no effect on the average onset latency because it would reflect the shortest latencies, regardless of distribution. This sensitivity to different aspects of the distribution of latencies across trials could, potentially, explain the RT/N2pc differences seen in the present work[9].

The results illustrated in Figures 3.2 (lower panel) and 3.3 allow for an unbiased comparison between the RT and N2pc measures (i.e., to compare onsets in both cases). To produce Figure 3.3, we calculated the latency of RTs in a way that was homologous to that used for the N2pc. We generated a frequency distribution of RTs (10-ms bins) for each observer, separately for each lag. The resulting three distributions, averaged over observers, are illustrated in Figure 3.3 where the abscissa represents time from T2 onset and the ordinate represents the percentage of total trials, separately for each lag. Upon inspection, it is clear that the functions for Lags 0 and 7 differ from one another by considerably more than 30 ms, at any arbitrary value of the ordinate. Thus, the magnitude of the postponement in RT is still greater than the corresponding postponement in N2pc even when the RT and N2pc latencies are computed in similar ways.

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[9] We thank Eric Ruthruff for pointing out this possibility.
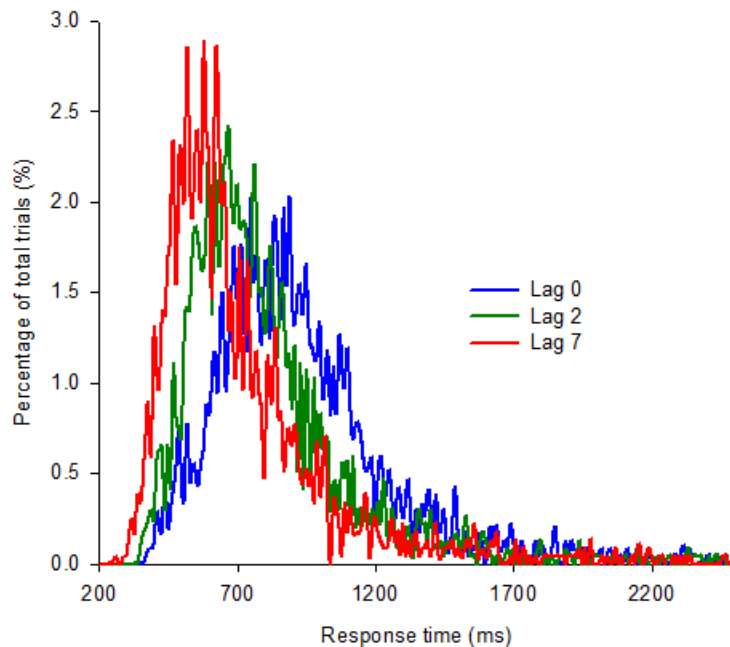
Figure 3.3. Grand-averaged frequency distribution of T2 RTs time-locked to the onset of the T2 search array, separately for Lags 0, 2, and 7. The abscissa represents time from T2 onset and the ordinate represents the percentage of total trials.

3.6.1. One Source of Delay or Many?

Clearly, the estimates based on N2pc and RT cannot always be regarded as measures of the same thing. Rather, the substantial difference in the N2pc and RT measures obtained in the present study may reflect AB-related delays at different stages of processing: deployment of attention to the target in the search display (indexed by the N2pc), and processes that occur after the target has been located, such as extraction of task-relevant information and response planning (included in the RT).

These findings have direct implications for theories of the AB. In most current accounts, the AB deficit is attributed to limitations in the transferring of T2 information into visual short-term memory (VSTM). Some theories (e.g., Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; Shih, 2008; Wyble, Bowman, & Nieuwenstein, 2009) postulate an explicit bottleneck at the input to VSTM. Other theories (e.g., Di Lollo, Kawahara, Ghorashi, & Enns, 2005; Olivers, van der Stigchel, & Hulleman, 2007), ascribe the AB to a failure of attentional control.

A common characteristic of all these theories is that the AB arises from events that occur at a single step in the chain of information processing. In contrast to this single-factor view, the present results suggest that the AB arises from bottlenecks and delays at more than one level within the system. This goes against the idea that processing of T2 cannot begin until all attributes of T1 have been processed. Rather, processing of some T2 attributes that require attention could begin when the processing of the corresponding attributes of T1 have been completed. This idea entails a concurrent/successive sequence of processing wherein higher-level processing of some stimulus attributes is initiated even while lower-level processing of other attributes is still under way. Such a system would be compatible with Awh et al.'s (2004) multi-channel account of the AB deficit.

An important consideration regarding the factors that influenced the latency of the N2pc in the present experiment is that a task switch occurred between T1 and T2. It has been hypothesized that "the locus of task-switching interference is located at an early, perceptual level, whereas AB deficits take place at a late, central level" (Vachon, Tremblay, & Jones, 2007, p. 345). On this hypothesis, task switching and the AB are regarded as independent events, with the latency of the N2pc being governed by a task switch, and the accuracy (or the latency) of T2 identification being governed by other factors that produce the AB deficit (Vachon & Jolicœur, 2011; Vachon et al., 2007). On this view, the N2pc would not have been delayed in the absence of a task switch[10]. This proposal, however, cannot be verified on the basis of extant empirical evidence because all the studies in which the N2pc was investigated throughout the period of the AB employed paradigms that involved task switching (Akyürek et al., 2010; Brisson & Jolicœur, 2007; Corriveau et al., 2012; Dell'Acqua et al., 2006; Jolicœur et al., 2006a, b; Lien et al., 2011; Pomerleau et al., 2014; Robitaille et al., 2007; Verleger et al., 2012). At any rate, Vachon et al.'s hypothesis of independence needs to be viewed in the context of input-control theories such as Boost and Bounce (Olivers et al., 2007) and Temporary Loss of Control (Di Lollo et al., 2005) in which task switching and the AB are not regarded as independent. According to these theories, the critical factor in the AB is a task switch between T1 and the ensuing distractor. Thus, a delay of the N2pc during the period of the AB should be observed even in the absence of a task switch between T1 and T2.

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[10] We thank an anonymous reviewer for raising this possibility.

3.6.2. Is Attention Involved in Pop-Out Search?

The type of search task used in the present work is known as "oddball search" because on any given trial the search array contained a target that differed in only one dimension (colour, in this case) from the remaining items. There has been disagreement as to whether the detection of oddball targets requires attention or whether such targets are processed preattentively because they "pop out".

The preattentive option emerged from the finding that RTs to pop-out targets are invariant with the number of distractors in the search display (e.g., Egeth, Jonides, & Wall, 1972; Treisman & Gormican, 1988). The alternative option, that pop-out search involves attention, emerged from two related findings. First, that responses to pop-out targets can be primed, thus implicating attention (Maljkovic & Nakayama, 1994, 1996). Second, that the processing of pop-out targets is impaired during the period of the AB, again pointing to the involvement of attention (Joseph et al., 1997). Our findings that both the latency of the N2pc and the RT to T2 were affected by the AB are clearly in line with the option that pop-out search involves attention.

3.6.3. Concluding Comments

In summary, the present work is characterized by three main themes. First, by adducing electrophysiological evidence, we substantiated Ghorashi et al.'s (2007) claim that visual search is postponed during the period of the AB. Second, the discrepancy between the behavioural and the electrophysiological estimates of the AB-related delay (about 300 ms and 30 ms, respectively), pointed to multiple sources of delay (or multiple bottlenecks) along the chain of processing events. Finally, the present finding that the latency of the N2pc is increased during the period of the AB is clearly consistent with the idea that attention is involved in the processing of pop-out stimuli.

3.7. Appendix

Here we provide an account of the significant effect of Lag revealed in the analysis of the mean amplitudes of the ERP components.
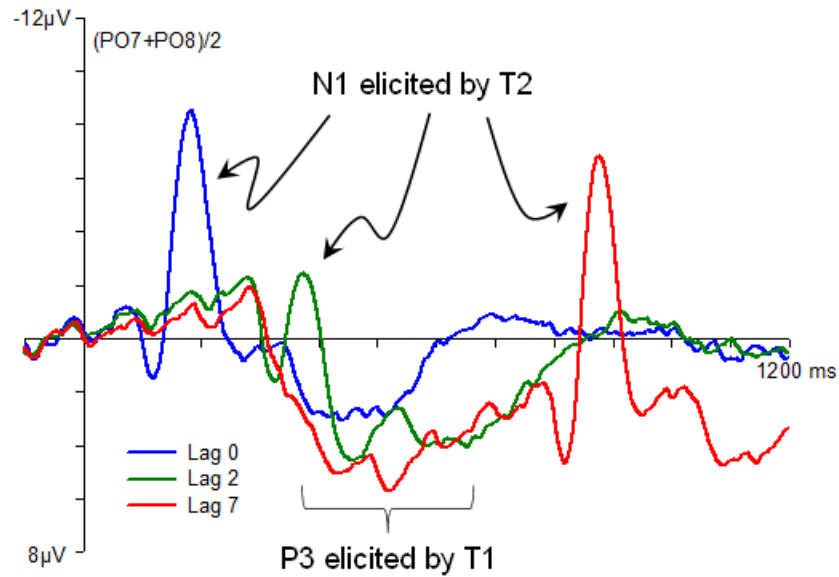
Figure 3.4. **Grand-averaged ERPs measured at posterior electrodes PO7/8 time-locked to the onset of the T1 stimulus, separately for Lags 0, 2, and 7.**

Figure 3.4 shows the grand-averaged ERPs measured at electrodes PO7/8, time-locked to the onset of the T1 stimulus, separately for Lags 0, 2, and 7. The figure illustrates how the overall level of ERP components elicited by T2 can be affected by temporal overlap with ERP components elicited by T1. The important point to bear in mind is that the temporal separation between T1 and T2 differs as a function of lag. Therefore, the overlap between the ERP components elicited by T1 and T2 will also differ as a function of lag. How these temporal contingencies affect the overall level of the T2-elicited ERPs can be best seen in the level of the T2-elicited N1 as a function of its temporal overlap with the T1-elicited P3.

At Lag 0 the T2-elicited N1 occurs before the T1-elicited P3, hence its level is virtually unaffected. By the same token, at Lag 7 the N1 occurs after the P3, and its level is similarly unaffected. At Lag 2, however, the timing of the T2-elicited N1 coincides with that of the T1-elicited P3, thus causing the overall level of the ERP in the N1 time-range to become more positive. The same considerations apply to the overall level of the ERP components involved in the computation of the N2pc (Figure 3.2, top panel). The effects of overlapping components on overall level resulted in the significant effect of Lag revealed in the analysis of the mean amplitudes of the ERP components in the latency

range of the N2pc. It should be emphasized that, because it is displayed foveally, T1 does not elicit lateralized ERP components. Given the lateralized nature of the N2pc, this rules out the possibility that any T1-elicited component may have affected the T2-elicited N2pc.

Chapter 4.

Perception of temporal order during the attentional blink: using stimulus salience to modulate prior entry[11]

4.1. Preface

Considered collectively, the results presented in the previous chapters provide mixed evidence about whether salience is impaired by the availability of attention. The results of the experiments reported in Chapter 2, in which pop-out search efficiency was invariant with lag, seem to suggest that salience information is available, and can be used just as efficiently throughout the period of the AB. The results of Chapter 3, however, indicate that the latency of attentional selection (as indexed by the N2pc) of a salient stimulus is delayed during the period of the AB, and, in both chapters, the behavioural report of a salient stimulus (RT to the presence of a salient oddball) is greatly delayed during the period of the AB.

In the current chapter we employed a different way of assessing whether salience is impaired throughout the period of the AB. First, instead of the salient target appearing within a spatial search array, as in the previous chapters, the salient target in the present chapter was presented within the RSVP stream. Second, a different dependent measure was employed – perception of temporal order – because salience is known to affect perception of temporal order (e.g., Donk & Soesman, 2011). We examined how salience affects the perception of temporal order throughout the period of the AB, in order to determine whether salience is affected by the availability of attention. If salience is unimpaired during the period of the AB, it should equally modulate the perception of temporal order throughout the period of the AB. If salience is impaired when attention is less available, however, the effect of salience on the perception of temporal order should be reduced inside, relative to outside, the period of the AB.

4.2. Abstract

When multiple targets are presented in rapid sequence, observers frequently confuse the order in which they were presented. The probability of order reversals is known to vary throughout the period of the attentional blink (AB), which refers to an impairment in the perception of the second of two targets when it is presented within about 500 ms from the first. Our objective was to examine the principle of prior entry (in which perception of temporal order is said to be affected by the relative latency at which each target is processed) as a determinant of the perception of temporal order throughout the AB. In two experiments, three letter targets (T1, T2, T3) were inserted in a stream of digit distractors, with T3 always presented directly after T2. The T1-T2 lag was varied to assess the perception of T2-T3 temporal order throughout the period of the AB. Processing latency was manipulated by means of salience. In Experiment 4.1, salience of T2 and T3 was manipulated exogenously by coloring the salient target red with all other stimuli being green. In Experiment 4.2, salience was modulated endogenously by manipulating which of the two targets matched the contents of working memory. Consistent with the principle of prior entry, perception of temporal order in both experiments was enhanced throughout the period of the AB when T2 was salient, and impaired when T3 was salient. Simulations based on the Episodic Simultaneous Type, Serial Token (eSTST) model that incorporates prior-entry, matched the empirical results.

4.3. Introduction

When two stimuli are presented in rapid sequence, observers frequently confuse the order in which they were presented. Among the factors thought to determine the perception of temporal order is the relative amount of attention deployed to the stimuli. That is, the perception of temporal order of two sequential stimuli is determined not only by the actual order of presentation but also by the relative amount of attention deployed to the stimuli (e.g., Reeves & Sperling, 1986). Thus, a well-attended temporally-trailing stimulus may be perceived as having occurred earlier than a less-attended stimulus that was actually presented first. This is known as the principle of prior entry (Spence & Parise, 2009; Titchener, 1908)[12]. There is an abundance of findings which show that prior entry can be elicited by peripheral as well as central cues or exogenous as well as endogenous attention (e.g. Shore, Spence & Klein, 2001).

On the face of it, the role of attention in the perception of temporal order could be examined with a paradigm known as the attentional blink (AB). Originally demonstrated by Raymond, Shapiro, and Arnell (1992), the AB refers to an impairment in identification accuracy for the second of two targets (T2) when it is presented within about 500 ms from the first (T1). Conventionally, the two targets are inserted in a stream of distractors presented in rapid serial visual presentation (RSVP). The T2 deficit has been ascribed to an uneven deployment of attention during the period of the AB, when attention is deployed to T1 to the detriment of T2.

As for the perception of temporal order, there is evidence that, despite instructions to report T1 and T2 in the order in which they were presented, observers often report them in the reverse order, with the frequency of reversals being highest when T2 is presented directly after T1, in the RSVP position known as Lag 1 (Akyürek et al., 2012; Akyürek & Hommel, 2005; Akyürek, Riddell, Toffanin, & Hommel, 2007;

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[12] There is an interesting and enduring discussion as to whether or to what extent prior entry reflects judgment biases or reflects the influence of attention on processing rate (e.g. Jaskowski, 1993; Shore, Spence, & Klein, 2001; Spence, Shore, & Klein, 2001). Also whether any changes in processing rate involve the attended or the unattended item (e.g., Tünnermann, Petersen & Scharlau 2014; Weiss, Hilkenmeier & Scharlau 2013). The assumption is made in the present work that prior entry speeds up the processing of the attended item. A detailed discussion of these issues, however, would be beyond the scope of the present work. This is because the principal objective of the present study was not to examine the mechanisms underlying prior entry but to determine whether prior entry affects the perception of temporal order throughout the course of the AB.

Chun, 1997; Chun & Potter, 1995; Hilkenmeier, Scharlau, Weiss, & Olivers, 2012; Isaak, Shapiro, & Martin, 1999; Olivers, Hilkenmeier, & Scharlau, 2011; Spalek, Falcon, & Di Lollo, 2006). Interpretation of this finding, however, is complicated by a confounding factor. Namely, as the intertarget lag is increased, the temporal separation between the two targets increases correspondingly, making the targets more temporally distinct from one another. The improved perception of temporal order as the inter-target lag is increased would then be attributable to increased ease of temporal discriminability rather than to improved ability to maintain temporal order.

To determine whether the perception of temporal order is impaired during the period of the AB, it is necessary to keep the temporal discriminability of the two targets constant throughout that period. This was done by Spalek, Lagroix, Yanko, and Di Lollo (2012) who used a variant of the AB paradigm in which three letter targets (T1, T2, T3) were inserted in an RSVP stream of digit distractors. The temporal lag between T1 and T2 was either 100, 200, or 700 ms (Lags 1, 2, and 7). Critically, T3 was always presented directly after T2. This permitted an assessment of T2-T3 order errors throughout the period of the AB (i.e., at each T1-T2 lag). The highest frequency of order errors was observed at Lag 2, with Lags 1 and 7 showing considerably fewer reversals.

Spalek et al. (2012) offered a theoretical account of their results in terms of the Episodic Simultaneous Type, Serial Token (eSTST) model of Wyble, Bowman, and Nieuwenstein (2009), which incorporates the principle of prior entry. Other models have been proposed that also utilize prior entry to account for order reversals. Notably, Hilkenmeier, Scharlau, Weiss, and Olivers (2012) proposed a simple computational model similar to Olivers and Meeter's (2008) Boost-and-Bounce theory, to account for order reversals of two sequential targets inserted in an RSVP stream of distractors. Two things should be noted about this model: first, its predictions were examined only for Lag 1; second, the main conclusion was that the tenets of the model were consistent with a range of other theories that postulate transient attention as the mechanism underlying order reversals (e.g., Shih, 2008; Olivers & Meeter, 2008; Wyble et al., 2009).

Any of these models would provide a suitable conceptual framework for the present work, whose main objective was to study the relationship between prior entry and the AB. We opted for the eSTST model for two reasons: first, it has been implemented not only for Lag 1, but for lags throughout the period of the AB and,

second, it has been used successfully to predict the outcomes of other AB experiments (e.g., Spalek et al., 2012; Lagroix, Spalek, Wyble, Jannati, & Di Lollo, 2012). A brief outline of the eSTST model will show how it accounts for the results of Spalek et al., and will provide the conceptual background for the present work.

At the most basic level, eSTST makes use of a two-stage architecture similar to that of Chun and Potter's (1995) two-stage theory and adopts the type-token distinction introduced by Kanwisher (1987). In the first stage (the input layer), abstract identity information about each stimulus (its type) is extracted. For a stimulus to be reported correctly, however, it must gain access to a later encoding stage where its identity information is bound to a token and is thereby encoded into working memory.

For a type representation to be bound to a token, it must be enhanced by a transient attentional mechanism (the blaster) that amplifies the strength of the type signal. This mechanism is triggered upon detection of a target, and its activity lasts for approximately 200 ms. An inhibitory phase then follows, during which attention (i.e., the blaster) is suppressed while the target undergoes the binding process. This T1- triggered suppression of attention extends over several hundred milliseconds and mediates the AB by preventing the T2 type from being bound to a token until T1 tokenization is complete. This delay in T2 processing leaves it vulnerable to decay and interference by trailing items. On the other hand, if T2 is presented during the excitatory period of the blaster's activity triggered by T1 (i.e., if it is presented within the same attentional episode as T1), its signal will be amplified. This will result in T2 preceding the inhibitory phase, thus avoiding the AB deficit, a phenomenon known as Lag-1 sparing. This sequence of processing events culminates with the production of tokens in working memory. Each token has its own unique time stamp which determines the order in which it is perceived.

Within eSTST, two main factors are said to govern the perception of temporal order. First, temporal order is determined both by the order in which the targets were presented and by their relative strength. This is because stronger types are tokenized faster thus increasing the probability of gaining earlier access to working memory. Second, the strength of a type is determined by the degree of enhancement received from the blaster, that is, the amount of attention deployed to it. In essence, eSTST handles the perception of temporal order according to the principle of prior entry which

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states that attention affects the latency of target processing (Maylor & Hockey, 1985; Töllner, Zehetleitner, Gramann, & Müller, 2011; but see Stelmach & Herdman, 1991, for a more complex view of the effects of attention on stimulus processing).

On this principle, any manipulation that causes a greater amount of attention to be deployed to the second of two successive targets will (a) increase its signal strength, which will (b) decrease its processing latency, leading to (c) increased probability of order reversals. Spalek et al. (2012) tested this conjecture by manipulating the latency of attention deployment to two successive targets (T2 and T3, as noted above) in two ways. One way was to manipulate the presence/absence of distractors intervening between T1 and T2 in the RSVP stream. The sequence of events is illustrated in Figure 4.1. When distractors are present (Figure 4.1.A), the deployment of attention to T2 (i.e., the onset of the blaster) is delayed relative to when the distractors are absent (Figure 4.1.B). The delay is shown by the time difference between the two vertical segmented lines in Figure 4.1. This delay results in less attention being deployed to T2 than to T3, causing the strength of the T3-type signal to be enhanced, with a corresponding increment in the probability that T3 is tokenized before T2 (see Figure 4.1.A). The upshot is increased frequency of reversals when distractors are present.

The second way in which the latency of attention deployment was manipulated in the Spalek et al. (2012) study was by varying the T1-T2 lag. In terms of eSTST, this manipulation affects the suppression of the blaster. At short lags, the blaster is suppressed while T1 is being tokenized. This means that the deployment of attention to T2 is delayed, resulting in less attention being deployed to T2 relative to T3. The consequences for the perception of temporal order are the same as for the distractor manipulation described above.

In both these cases (presence/absence of distractors and inter-target lag), the relative strengths of the T2 and T3 signals were manipulated indirectly by events that preceded the T2-T3 pair. In the present work we manipulated the salience of the stimuli themselves in order to test the principle of prior entry in a different – and more direct – way.
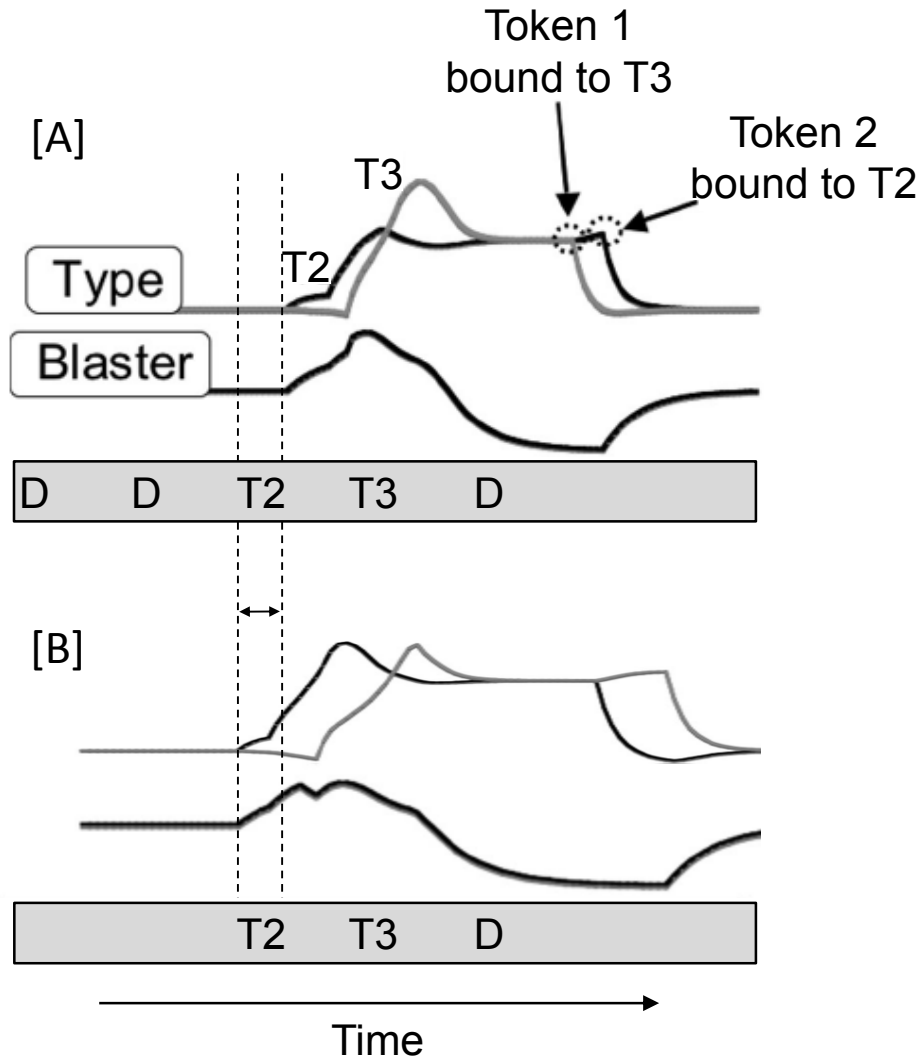
Figure 4.1. Schematic depiction of the activation of the blaster and type nodes in the eSTST model in response to two sequential targets (T2, T3). Modified from Figures 12 and 16 of Wyble et al. (2009). (A) Example of a trial on which distractors precede T2. The onset of the blaster is delayed relative to when distractors are absent, resulting in less attention being deployed to T2 than to T3, thus causing the strength of the T3-type signal to be enhanced. The enhanced strength of T3 causes it to complete the token-binding process before T2. The outcome of this trial would be that both T2 and T3 are reported but in the wrong order. (B) Example of a trial on which there are no distractors preceding T2. The onset of the blaster is not delayed, resulting in similar amounts of attention being deployed to T2 and T3. The comparable strengths of the targets cause them to be tokenized in the order of their presentation. The outcome of this trial would be that T2 and T3 are reported in the correct order. The delay in the onset of the blaster caused by the presence of distractors preceding T2 is shown by the time difference between the two vertical segmented lines. T = target; D = distractor.

The plan was to manipulate prior entry by varying the relative salience of two sequential targets. We followed Fecteau and Munoz (2006) who defined salience as that property of a stimulus that causes it to be processed faster than a non-salient stimulus. In the present work, we manipulated the relative salience of T2 and T3 within the three-target AB paradigm employed by Spalek et al. (2012). In Experiment 4.1, we manipulated salience exogenously by varying a physical property of the stimuli (their color). In Experiment 4.2 we manipulated salience endogenously by exploiting the finding that attention is deployed more rapidly to a stimulus when it matches a representation in working memory (e.g., Downing, 2000; Soto, Heinke, Humphreys, & Blanco, 2005).

As noted above, it has been known for some time that (a) prior entry can be affected by exogenous as well as endogenous attention (e.g., Shore, Spence, & Klein, 2001), (b) that order errors happen in the AB (e.g., Spalek et al., 2011), and (c) that salience affects prior entry (e.g., Donk & Soesman, 2011). The novel contribution of the present work is that these factors were examined in combination. Namely, the effects of exogenous and endogenous manipulations of salience on the perception of temporal order were examined throughout the period of the AB.

4.4. Experiment 4.1

In Experiment 4.1 we manipulated salience of the target stimuli by means of color. It is known that attention is deployed more quickly to (a) red than to green stimuli (Fortier-Gauthier, Dell'Acqua, & Jolicœur, 2013) and (b) to singleton than to non-singleton items (Theeuwes, 1992). With these considerations in mind, either T2 or T3 was made more salient by making it a red singleton amongst green items. In a baseline condition both T2 and T3 were green, as the rest of the stream, making them equally salient. This resulted in three conditions (baseline, T2 salient, T3 salient) that were crossed with lag (Lags 1, 2, and 7; see Figure 4.2). Based on the principle of prior entry, we expected the frequency of order reversals to vary with target salience. Fewer order reversals relative to baseline should be in evidence when T2 is salient, and more when T3 is salient.
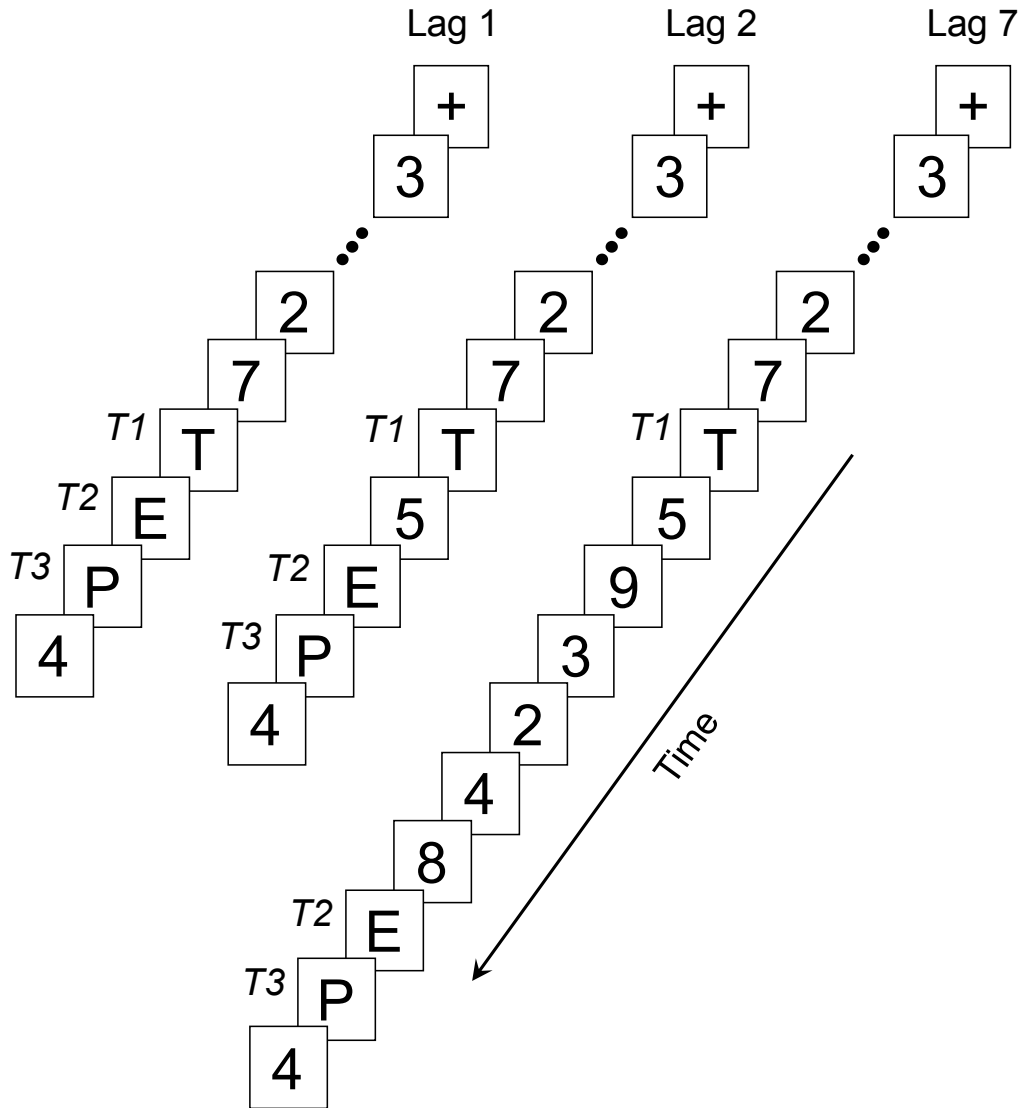
Figure 4.2. **Schematic representation of the sequence of events within a trial for each lag in Experiment 4.1. All items were green, except for T2 and T3 one of which was sometimes red on any given trial.**

These predictions were instantiated in the simulation of the eSTST model, illustrated in Figure 4.3.A. The simulations were obtained using the same model and parameters as were used by Wyble et al. (2009), with the exception that the effect of salience was simulated by adding a constant of 0.2 to the input-strength value of the salient target[13]. This value was chosen a priori by the lead author of Wyble et al. (2009)

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[13] As in the study by Spalek et al. (2012), Lag 3 was used instead of Lag 2 in the simulations because, in the present version of eSTST, the transient attentional window that determines the signal strength of items encoded in working memory is probably a little too broad in comparison with the data. This, however, must be regarded as merely a matter of parameter adjustment rather than a fundamental flaw with the model.

in advance of seeing the results, on the assumption that the representation of the salient target would be moderately stronger at the input level. The results of the simulation were consistent with the principle of prior entry: salience affected the probability of reversals at every lag in the predicted direction.
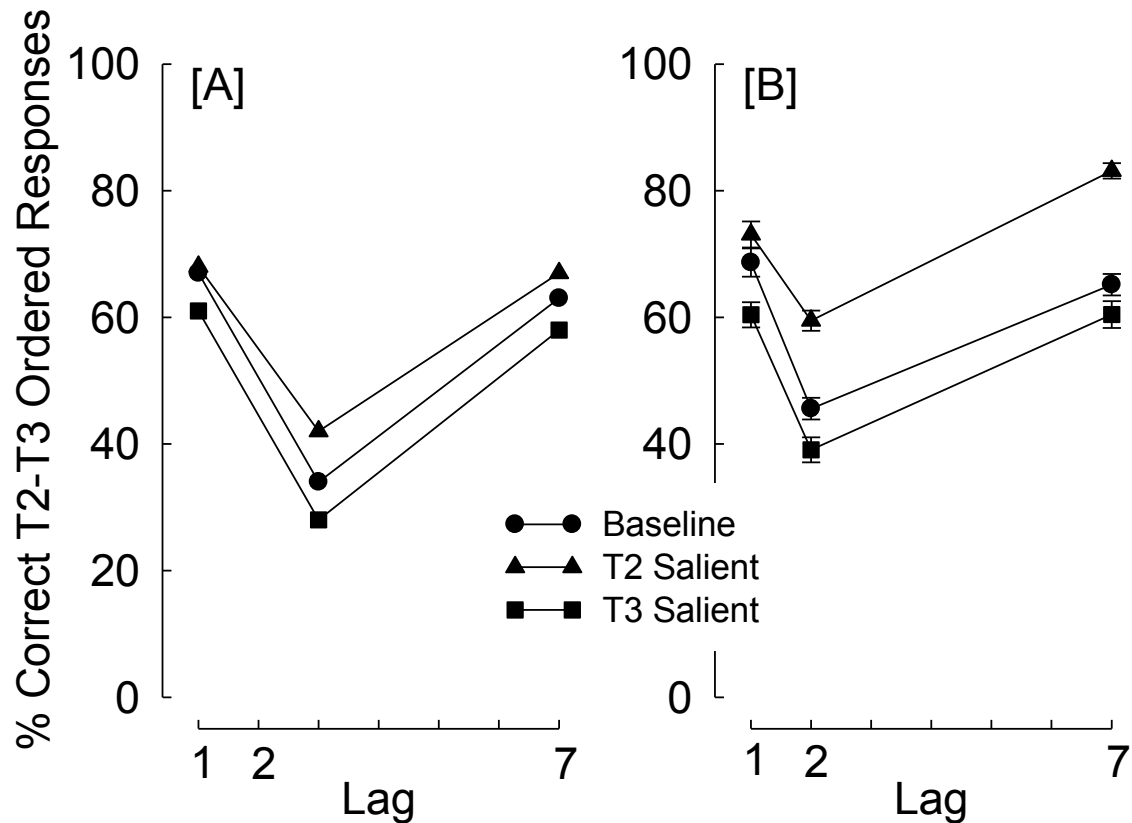
Figure 4.3. **(A) Simulated results of correct T2-T3 ordered responses for Experiment 4.1, based on the eSTST model (Wyble et al., 2009); (B) Percentage of correct T2-T3 ordered responses in Experiment 4.1, only for trials in which all three targets were reported   correctly and T1 was reported first. Error bars indicate standard error of the mean.**

4.4.1. Methods

Participants

Fifty-seven volunteers participated for class credit or payment. All reported normal or corrected-to-normal vision and were naive to the purpose of the experiment.

Apparatus and Stimuli

The stimuli consisted of sequences of digits (2–9) and three letters (T1, T2, T3; all uppercase letters of the English alphabet, except I, O, Q, and Z) presented in RSVP in the centre of a computer monitor. All digits, as well as T1, were green (CIE x/y values: 287/.627; luminance: 31.0 cd/m2, as measured by a Minolta CS 100 Chroma Meter). In the baseline condition T2 and T3 were also displayed in green. In the T2-salient condition, T2 was colored red (CIE x/y values: .646/.336; luminance: 32.2 cd/m2) and T3 green. The reverse was true in the T3-salient condition. All stimuli subtended approximately 0.5° of visual angle vertically, and were presented on a white background (CIE x/y values: .308/.333; luminance: 154 cd/m2). Observers sat in a dimly lit room, and viewed the displays binocularly from a distance of approximately 60 cm.

Procedure

At the beginning of a session, observers were required to read the instructions displayed on the screen, and were invited to ask questions to clarify procedural points. At the beginning of each trial, a small green fixation cross was presented in the center of the screen, indicating the location at which the RSVP stream of digits and letters was about to appear. Observers initiated each trial by pressing the space bar. The RSVP stream of digits and letters was displayed directly afterward. Each item in the RSVP stream remained on the screen for 100 ms, and was replaced immediately by the next item, yielding a presentation rate of 10 items/s.

The RSVP stream contained a variable number of digit distractors and three letter targets, selected randomly, without replacement, from the pool of letters. The number of distractors preceding the first target was determined randomly on each trial and varied between 5 and 10. On any given trial, the distractors were selected randomly, with replacement, from the pool of digits, with the constraint that the selected digit was not one of the two preceding items.

Three targets were inserted in the RSVP stream. T1 was presented directly after the last distractor in the leading stream. T2 was then presented at one of three lags after the onset of T1: 100 (T2 presented directly after T1), 200, or 700 ms. Digit distractors continued to be presented during the two longer intertarget lags. T3 was always presented directly after T2 and was followed by one digit-distractor that acted as a mask

(see Figure 4.2.). Observers were required to report the identity of the three targets in the order in which they were presented by pressing the corresponding keys on the keyboard. They were informed that the first letter would always be green, and that either the second or third letter might be red or that both could be green. The combination of the T2-T3 colors was determined randomly on each trial, with the constraint that there were an equal number of trials for each T2-T3 color combination, at each of the three lags.

There were 9 practice trials at the beginning of the session. These were followed by a total of 360 trials, 40 for each of the nine combinations of Salience (Baseline, T2 Salient, T3 Salient) and Lag (1, 2, 7). The nine combinations were presented randomly intermixed across trials.

4.4.2. Results and Discussion

Identification Accuracy

Identification accuracy (and associated standard error) for the three targets, averaged over observers, separately for each combination of Salience and Lag, is presented in Table 4.1. The values for T2 and T3 were conditionalized on the correct report of all leading targets on that trial.

Given that the main focus of the present work was the perception of temporal order as distinct from identification accuracy, no statistical analyses were performed at this point, except to verify that an AB was obtained. This was done by comparing mean T2 accuracy (given correct report of T1) for Lags 2 and 7 in all three conditions. The analysis revealed significant AB deficits (T2 accuracy lower at Lag 2 than at Lag 7, see Table 4.1) in all conditions: Baseline: $t(56) = 9.39$, $p < .001$, T2 Salient: $t(56) = 10.51$, $p < .001$; T3 Salient: $t(56) = 7.97$, $p < .001$.

Table 4.1. Percentage of correct identifications of the three targets (and standard error of the mean)

		T1	T2|T1	T3|T1&T2
Experiment 1				
Baseline	Lag 1	75 (1.6)	89 (1.1)	72 (1.9)
	Lag 2	85 (1.4)	57 (1.6)	73 (1.8)
	Lag 7	86 (1.4)	76 (1.5)	89 (1.2)
T2 Salient	Lag 1	70 (1.9)	93 (0.8)	70 (1.9)
	Lag 2	85 (1.3)	71 (1.8)	73 (2.0)
	Lag 7	86 (1.4)	91 (0.9)	83 (1.4)
T3 Salient	Lag 1	74 (1.7)	86 (1.2)	81 (1.4)
	Lag 2	84 (1.5)	53 (2.3)	83 (1.7)
	Lag 7	87 (1.4)	73 (2.0)	94 (0.7)
Experiment 2				
Baseline	Lag 1	79 (2.1)	87 (1.4)	76 (2.1)
	Lag 2	86 (1.6)	61 (2.2)	72 (2.6)
	Lag 7	88 (1.4)	81 (2.1)	88 (1.2)
T2 Salient	Lag 1	76 (2.0)	96 (0.9)	70 (2.5)
	Lag 2	85 (1.9)	88 (2.3)	66 (2.7)
	Lag 7	85 (1.7)	94 (1.2)	85 (1.6)
T3 Salient	Lag 1	76 (2.2)	85 (1.6)	93 (2.1)
	Lag 2	83 (1.9)	53 (2.8)	93 (1.6)
	Lag 7	86 (2.0)	74 (2.3)	96 (1.0)

Perception of Temporal Order

The main objective of the present work was to assess the effect of the relative salience of T2 and T3 on the perception of T2-T3 temporal order at different T1-T2 lags. For this purpose, it is necessary to consider only trials in which all three targets are reported correctly. The reasoning is as follows: In order to be confident that an AB occurred on any given trial, T1 must be reported correctly. Then, to assess the perception of temporal order in the T2-T3 pair, both targets must also be reported correctly. Namely, if only one of them is reported correctly it would be unclear whether or not it had been seen in the correct temporal order. For example, if T2 is missed, the

observers might opt to begin their report with the two items of which they are sure (T1 and T3, in this example) and then go on to guess the third item. In this example, T3 was perceived in the correct order but was reported in the incorrect order. Thus, the main requirement for scoring temporal order was that T1 be reported correctly in the first ordinal position and T2 and T3 be reported correctly regardless of order.

Each of the 57 observers contributed 40 trials at each of the nine combinations of Salience (Baseline, T2 Salient, T3 Salient) and Lag (1, 2, 7), for a total of 2,280 trials per cell. The number of trials on which all three targets were reported correctly with T1 in the correct position was 750, 721, and 1309 for Lags 1, 2, and 7, respectively, in the Baseline condition, 627, 905, and 1471 for Lags 1, 2, and 7, respectively, in the T2 Salient condition, and 780, 757, and 1340 in the T3 Salient condition. The functions in Figure 4.3.B illustrate the percentage of trials on which T2 and T3 were reported in the correct sequence, given correct identification of all three targets, separately for each condition, across lags. A 3 (Salience: Baseline, T2 Salient, T3 Salient) × 3 (Lag: 1, 2, 7) within-subjects analysis of variance (ANOVA) performed on the data in Figure 4.3.B yielded significant effects of Salience, $F(2, 112) = 71.37$, $p < .001$, MSE = 213.44, $\eta_p^2 = .560$, and Lag, $F(2, 112) = 99.66$, $p < .001$, MSE = 241.00, $\eta_p^2 = .640$. The interaction effect was also significant, $F(4, 224) = 5.08$, $p = .001$, MSE = 147.54, $\eta_p^2 = .083$.

To ascertain whether each of the two salience manipulations (T2 or T3 salient) differed significantly from baseline, we performed two additional planned comparisons. The T3-salient vs. Baseline ANOVA revealed significant effects of Salience, $F(1, 56) = 24.35$, $p < .001$, MSE = 147.95, $\eta_p^2 = .303$, and Lag, $F(2, 112) = 64.62$, $p < .001$, MSE = 269.06, $\eta_p^2 = .675$. The interaction effect was not significant ($F < 1$). The T2-salient vs. Baseline ANOVA revealed significant effects of Salience, $F(1, 56) = 56.00$, $p < .001$, MSE = 223.75, $\eta_p^2 = .500$, and Lag, $F(2, 112) = 84.14$, $p < .001$, MSE = 183.98, $\eta_p^2 = .600$. The interaction effect was also significant, $F(2, 112) = 8.67$, $p < .001$, MSE = 158.74, $\eta_p^2 = .134$. We pursued this significant interaction by performing individual t-tests between the mean for the Baseline condition and that for the T2-Salient condition, separately for each lag. The only comparison that failed to reach significance was at Lag 1, $t(56) = 1.39$, $p = .171$ (all other $ps < .001$). Two things should be noted in this respect. First, the difference between the T2-salient and the Baseline condition was numerically in the expected direction. Second, the difference between the T2-salient and the T3-salient conditions at Lag 1 did reach statistical significance ($t(56) = 4.65$, $p < .001$). These

observations are consistent with the idea that the salience manipulation affected the perception of temporal order throughout the period of the AB.

These statistical analyses confirm the graphical evidence in Figure 4.3.B that, relative to baseline, the perception of temporal order was more accurate when T2 was salient, and less accurate when T3 was salient. This pattern of results is consistent with the principle of prior entry which stipulates that perception of the temporal order of two targets is determined by their relative processing speed (here influenced by salience) as well as by the actual order of presentation. In the present experiment, salience and order of presentation worked in conjunction when T2 was salient (enhancing the perception of temporal order) but in opposition when T3 was salient (impairing the perception of temporal order).

It is clear from a comparison of Figures 4.3.A and 4.3.B that the effect of salience on the perception of temporal order was predicted accurately by the eSTST model. Remarkably, the simulated results provided an excellent match for the empirical results not only by showing that the three conditions differed from one another at each lag, but also by showing that the T2-Salient condition did not differ statistically from the Baseline condition at Lag 1. The simulated score for the T2-Salient condition at Lag 1 was only 1% higher than the corresponding score in the Baseline condition.

4.5. Experiment 4.2

As noted above, the eSTST model is an instance of a broader class of models based on the principle of prior entry (e.g., Reeves & Sperling, 1986). It can be inferred from that principle that salience should have similar effects on the perception of temporal order, whether it is manipulated exogenously or endogenously. The important consideration is that salience affects the latency of processing – and hence the perception of temporal order – regardless of the way in which it is manipulated. The present experiment was a test of this hypothesis.

Instead of manipulating salience exogenously, as in Experiment 4.1, in the present experiment we manipulated salience endogenously by exploiting the finding that attention is deployed more rapidly to a stimulus when it matches a representation in working memory (e.g., Downing, 2000; Soto, Heinke, Humphreys, & Blanco, 2005).

Accordingly, in the present experiment, all stimuli were presented in black, but T2-T3 salience was manipulated by presenting either the T2 or the T3 letter prior to the RSVP stream, as the fixation item instead of the cross used in Experiment 4.1. Participants were informed that this letter would match either the second or the third target letter in that trial. With these exceptions, all stimuli and procedures were the same as in Experiment 4.1.

Predictions stemming from the general principle of prior entry can be instantiated in the eSTST model. The present endogenous manipulation of salience can be modeled in eSTST by reducing the tokenization threshold of the salient target. In practice, this means that the salient target is tokenized more rapidly, thus increasing the probability of it being perceived as temporally leading. In the present simulation, illustrated in Figure 4.4.A, the tokenization threshold of the salient target was set at 70% of its non-salient value. As in Experiment 4.1, this value was chosen a priori by the lead author of Wyble et al. (2009) prior to seeing the results. This was done under the assumption that, while observers knew the identity of the salient target ahead of time, they still needed to encode other information, such as its temporal and spatial characteristics. This would have caused only a modest reduction in the amount of information in need of consolidation into memory.
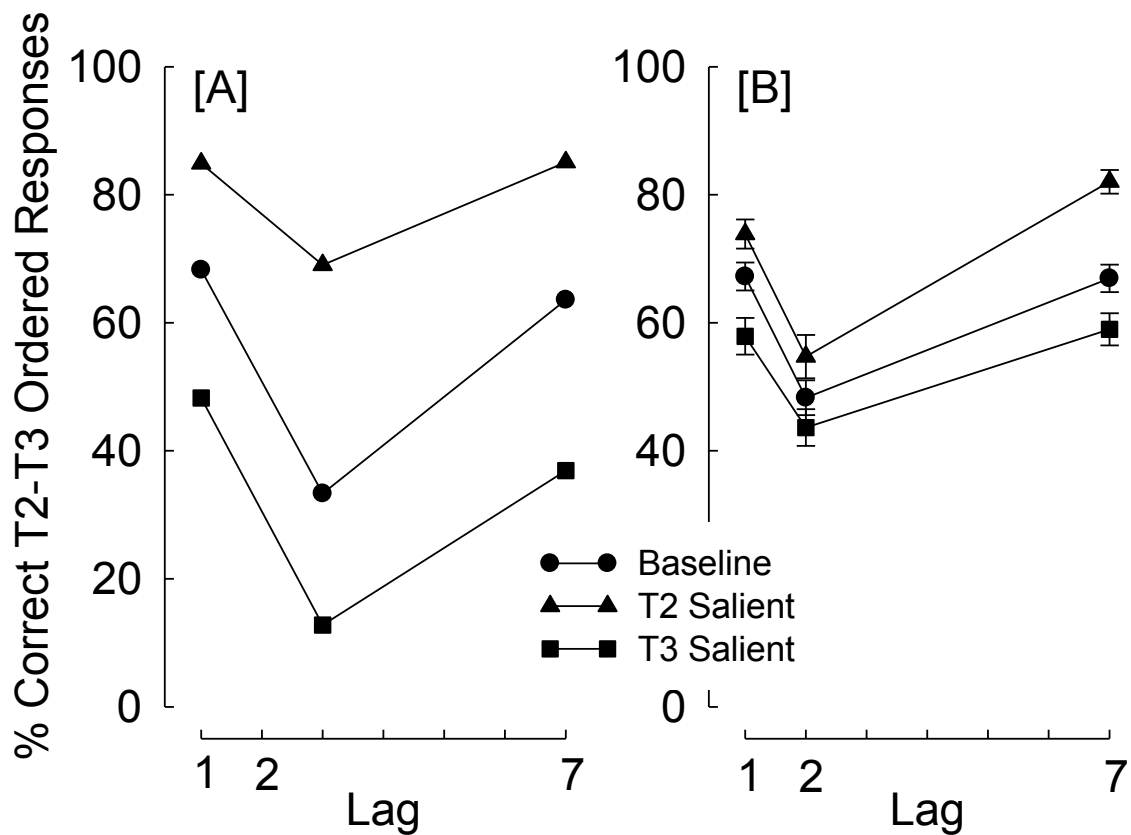
Figure 4.4. **(A) Simulated results of correct T2-T3 ordered responses for Experiment 4.2, based on the eSTST model (Wyble et al., 2009); (B) Percentage of correct T2-T3 ordered responses in Experiment 4.2, only for trials in which all three targets were reported correctly and T1 was reported first. Error bars indicate standard error of the mean.**

4.5.1. Methods

Participants

Thirty-five volunteers participated for class credit or payment. They were drawn from the same population as in Experiment 4.1.

Apparatus and Stimuli

The apparatus and stimuli were the same as in Experiment 4.1, with the exception that all stimuli were presented in black.

Procedure

The design and procedures were the same as in Experiment 4.1, with the following exceptions. In the Baseline condition, the fixation stimulus was the # symbol. Importantly, in the other two conditions, the fixation stimulus was a letter. Observers were instructed to attend to this letter because its identity would always be the same as one of either the T2 or T3 letters.

4.5.2. Results and Discussion

Identification Accuracy

Identification accuracy (and associated standard error) for the three targets, averaged over observers, separately for each combination of Salience and Lag, is presented in Table 4.1. As in Experiment 4.1, no statistical analyses were performed, except to verify that an AB was obtained. This was done by comparing the T2 means for Lags 2 and 7 in all three salience conditions. The analysis revealed significant AB deficits in all three conditions: Baseline: $t(34) = 9.06$, $p < .001$, T2 Salient: $t(34) = 3.84$, $p = .001$; T3 Salient: $t(34) = 7.56$, $p < .001$.

Perception of Temporal Order

Each of the 35 observers contributed 40 trials at each of the nine combinations of Salience (Baseline, T2 Salient, T3 Salient) and Lag (1, 2, 7), for a total of 1,400 trials per cell. The number of trials on which all three targets were reported correctly with T1 in the correct position was 482, 478, and 878 for Lags 1, 2, and 7, respectively, in the Baseline condition, 489, 551, and 862 for Lags 1, 2, and 7, respectively, in the T2 Salient condition, and 503, 465, and 781 in the T3 Salient condition. The functions in Figure 4.4.B illustrate the percentage of trials on which T2 and T3 were reported in the correct sequence, separately for each condition, across lags. A 3 (Salience: Baseline, T2 Salient, T3 Salient) × 3 (Lag: 1, 2, 7) within-subjects ANOVA performed on the data in Figure 4.4.B yielded significant effects of Salience, $F(2, 68) = 19.28$, $p < .001$, MSE = 381.96, $\eta_p^2 = .362$, and Lag, $F(2, 68) = 57.05$, $p < .001$, MSE = 224.25, $\eta_p^2 = .627$. The interaction effect was also significant, $F(4, 136) = 3.05$, $p = .019$, MSE = 127.12, $\eta_p^2 = .082$.

To ascertain whether the results of each of the two salience manipulations (T2 or T3 salient) differed significantly from baseline, we performed two additional planned comparisons. The T3-salient vs. Baseline ANOVA revealed significant effects of Salience, $F(1, 34) = 8.50$, $p = .006$, MSE = 331.37, $\eta_p^2 = .200$, and Lag, $F(2, 68) = 30.73$, $p <.001$, MSE = 214.43, $\eta_p^2 = .475$. The interaction effect was not significant ($F<1$). The T2-salient vs. Baseline ANOVA revealed significant effects of Salience, $F(1, 34) = 26.36$, $p < .001$, MSE = 175.27, $\eta_p^2 = .437$, and Lag, $F(2, 68) = 53.67$, $p <.001$, MSE = 197.04, $\eta_p^2 = .612$. The interaction effect was also significant, $F(2, 68) = 3.59$, $p = .033$, MSE = 119.03, $\eta_p^2 = .096$. We examined this significant interaction by performing individual t-tests between the mean for the Baseline condition and that for the T2-Salient condition, separately for each lag. The only comparison that did not quite reach significance was at Lag 2, $t(34) = 1.85$, $p = .073$ (all other ps $< .02$). Paralleling the finding at Lag 1 in Experiment 4.1, the difference between the T2-salient and the Baseline condition, while only marginally significant, was numerically in the expected direction. In addition, the difference between the T2-salient and the T3-salient conditions at Lag 2 was found to be statistically significant ($t(34) = 2.22$, $p = .033$). These observations are consistent with the idea that the salience manipulation affected the perception of temporal order at Lag 2 just as it did at other lags throughout the period of the AB.

Considered collectively, these statistical analyses confirm the graphical evidence in Figure 4.4.B that, relative to baseline, the perception of temporal order was more accurate when T2 was salient, and less accurate when T3 was salient. As well as being consistent with qualitative predictions based on the principle of prior entry, this pattern of results is broadly consistent with the eSTST simulation illustrated in Figure 4.4.A. The differences in level between the simulated and the empirical outcomes clearly suggests the need for some adjustment in the parameters used in the simulation. For example, the 30% reduction in the tokenization threshold of salient targets is probably in need of reduction.

Combined Analysis of Experiments 4.1 and 4.2

The pattern of results in Experiment 4.2 (Figure 4.4.B) parallels that seen in Experiment 4.1 (Figure 4.3.B), strongly suggesting that, in accordance with the principle of prior entry, the effect of salience on the perception of temporal order is invariant with whether salience is manipulated exogenously or endogenously.

We explored the equivalence of the exogenous and the endogenous manipulations of salience in a separate ANOVA in which Experiment was entered as a between-subjects factor. The 3 within-subject (Salience: Baseline, T2 Salient, T3 Salient) × 3 within-subject (Lag: 1, 2, 7) × 2 between-subjects (Experiment: 4.1, 4.2) mixed-factors ANOVA revealed significant effects of Salience, $F(2, 180) = 74.29$, $p < .001$, MSE = 277.10 $\eta_p^2 = .452$, and Lag, $F(2, 180) = 145.18$, $p < .001$, MSE = 234.67, $\eta_p^2 = .617$. The Salience × Lag interaction effect was also significant, $F(4, 360) = 5.62$, $p < .001$, MSE = 139.83, $\eta_p^2 = .059$. Notably, neither the main effect of Experiment, nor any of the interactions involving Experiment were significant (all Fs < 1 except the three-way interaction which had $F < 1.9$). In view of the non-significant effect of Experiment and its interactions, we combined the data for Experiments 4.1 and 4.2 to produce Figure 4.5.
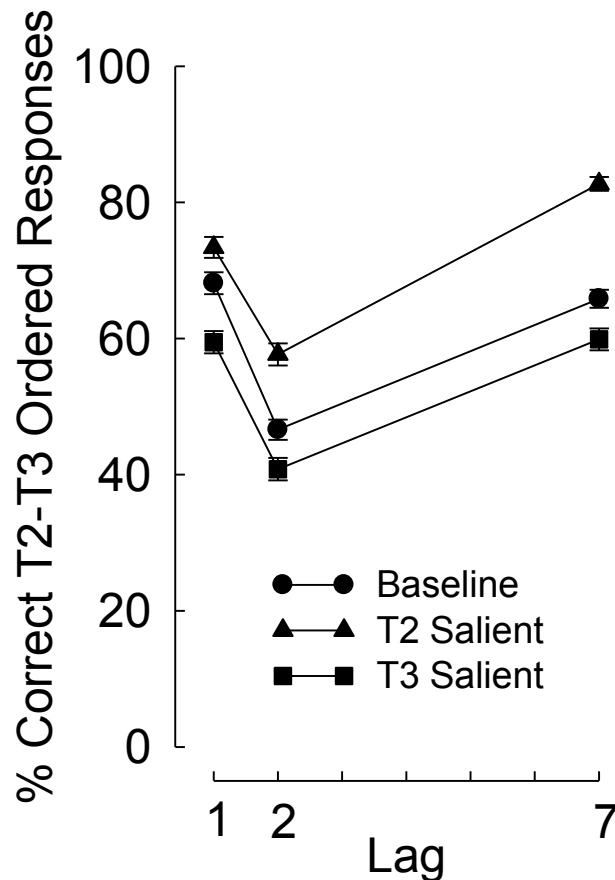
Figure 4.5. **Percentage of correct T2-T3 ordered responses, combined for Experiments 4.1 and 4.2, only for trials in which all three targets were reported correctly and T1 was reported first. Error bars indicate standard error of the mean.**

We pursued the significant interaction effect revealed in the combined ANOVA by performing individual t-tests among the three salience conditions, separately for each lag. All ps were < .004, except for the Baseline vs. T2-Salient comparison at Lag 1 (p = .020). The uniformly significant t-tests in the combined analysis contrast with the finding that some of the corresponding comparisons in the individual analyses of Experiments 4.1 and 4.2 failed to reach significance. A plausible suggestion is that the failures in the individual analyses might have arisen from lack of power. In this respect, it should be noted that, even when short of significance, the numerical ordering of the means was invariably in the expected direction.

Coupled with the graphical evidence in Figures 4.3.B and 4.4.B, the analysis involving both experiments confirms that the results of Experiment 4.2 matched those of Experiment 4.1 in most respects, despite the very different manipulations of salience. This correspondence is consistent with the hypothesis that the exogenous and endogenous manipulations employed in Experiments 4.1 and 4.2, operate in similar ways to affect the perception of temporal order throughout the period of the AB.

4.6. General Discussion

The main objective of the present work was to examine the principle of prior entry as it applies to the perception of temporal order of two rapidly sequential targets throughout the period of the AB. The principle of prior entry specifies that perception of temporal order is affected by the relative latency at which each target is processed. In the present work, latency was manipulated by means of salience. In Experiment 4.1, salience was manipulated exogenously by coloring the salient target red, with all other items colored green. In Experiment 4.2, salience was manipulated endogenously by varying which of two targets (T2 or T3) matched the contents of working memory. The results of both experiments were quite similar to one another: salience affected the perception of temporal order throughout the period of the AB. This pattern of results was consistent with qualitative predictions based on the prior-entry principle and with formal predictions from the eSTST model.

4.6.1. Theoretical Accounts of Perceived Temporal Order

The prior-entry account states that the perception of temporal order of two sequential targets is determined by two factors: the actual sequence in which the targets are presented and the latency of processing. On this reasoning, the present findings are explained on the grounds that these two factors worked in conjunction with one another when the salient stimulus was T2, but in opposition when it was T3. Besides being consistent with the general principle of prior entry, the results are successfully modeled by eSTST (Figures 4.3.A and 4.4.A).

An alternative account has been offered by Hommel and Akyürek (2005) in terms of episodic integration. The basic idea is that, given two targets presented in rapid sequence (T2 and T3 in the present case), the leading target opens an attentional gate that closes sluggishly, allowing the trailing target to slip through and become part of the same attentional episode. When that happens, accuracy of identification is high for both targets, but this comes at a cost: being part of the same attentional episode causes information about temporal order to be lost. As Hommel and Akyürek pointedly noted, "As subjects were able to correctly report both target identities both targets must have gained access to attentional resources. According to the sluggish-gate account this would mean that [T2 and T3] became part of the same attentional episode, which necessarily eliminated information about the sequence of the two stimuli.". An implication of this account is that perception of temporal order should be at chance (50%) whenever the targets are part of a single attentional episode.

The finding that the percentage of order reversals at Lag 2 was at approximately 50% in the Baseline condition (Figure 4.5.) is in line with predictions from the episodic integration account. However, this cannot be taken as unequivocal support for that account because the 50% level seen in the Baseline condition in Figure 4.5. may have arisen not from a loss of temporal order but from a systematically skewed ordering of T2 and T3 that happened to settle at 50%. This option is consistent with the present Lag-2 results for the T2-Salient and T3-Salient conditions, as well as with the results of Spalek et al. (2012) in which the percentage of order reversals fell significantly above as well as below 50% at Lag 2. Besides, as presently formulated, the episodic integration model cannot account for variation in order errors as a function of lag (Figure 4.5.). Given that (a) only trials on which both T2 and T3 were identified correctly were considered for the

analysis of order reversals, and that (b) T3 was always presented directly after T2, causing the two targets to be part of the same attentional episode, the probability of order reversals should have been invariant with lag. This invariance should also be true for other manipulations, notably salience, which is not part of the episodic integration model as presently formulated.

These considerations do not necessarily invalidate the episodic integration model. The model could be expanded in several ways to encompass the present results. For example, one possibility is for two attentional episodes to be initiated in quick succession. In this case, order information would be retained, bringing the accuracy of order information above chance level[14]. For such an account to be applicable to the present results, however, what needs to be articulated are the rules that govern when two stimuli become part of a single attentional episode or when they form two distinct episodes. What is also in need of explanation is how two distinct episodes can occur when the targets are presented in rapid succession (e.g., within ~100 ms) but not when they are separated by a longer interval (200-500 ms), as during the period of the AB.

4.6.2. Comparison with Earlier Work

The influence of exogenous and endogenous factors on accuracy of T2 identification in the AB was examined by Ghorashi, Enns, Spalek, and Di Lollo (2009) and by Ghorashi, Spalek, Enns, and Di Lollo (2009) using a cueing paradigm. The critical finding was that the effect of cueing – whether exogenous or endogenous – on accuracy of T2 identification was invariant across lags. That is, the effect of cueing was additive with the overall AB effect. The present results reveal a similar pattern of additivity: the effect of salience on the perception of temporal order was broadly additive with the overall AB effect (Figure 4.5.).

The present results are also consistent with those of Olivers, Hilkenmeier, and Scharlau (2011) who concluded that "… order reversals in the attentional blink are most parsimoniously explained through prior entry …" (p. 65). Because the manipulation of prior entry (by precuing) was implemented only at Lag 1, which is known to be a special case characterized by relative immunity from the AB deficit, those results cannot be

[14] We thank Elkan Akyürek for this suggestion.

regarded as addressing the issue of prior entry throughout the period of the AB. In contrast, our three-target design permitted an assessment of the effects of prior entry throughout the period of the AB, and provides support for the conclusion that the perception of temporal order throughout the AB is modulated by prior entry.

Chapter 5.

General Discussion

5.1. Summary

The role of attention in efficient pop-out search remains controversial. In the present work, to elucidate the role of attention in pop-out search, we manipulated the availability of attention for processing pop-out stimuli using an AB paradigm.

In Chapter 2, we examined whether the efficiency of pop-out visual search is impaired during the period of the AB. The main finding was that level of performance was impaired, but search efficiency was not. These findings suggest the action of at least two separable mechanisms, indexed by level and efficiency of pop-out search, which are affected in different ways by the availability of attention.

In Chapter 3, we examined the role of selective attention in pop-out search by measuring the onset latency of the N2pc, an event-related potential index of attentional selection. Both the RT and the N2pc measures were delayed during the AB, but the delay in N2pc was substantially shorter than that in RT (30 ms and 300 ms, respectively). This pattern of results points to multiple sources of delay in the chain of processing events, as distinct from the single source postulated in current theories of the AB. These results also strongly suggest that selective attention is involved in at least some aspects of the processing of pop-out search tasks.

Finally, in Chapter 4, we manipulated the relative exogenous and endogenous salience of two targets (T2, T3) presented throughout the period of the AB and measured perception of temporal order. Both exogenous and endogenous salience was found to be effective in modulating the perception of temporal order throughout the period of the AB. Consistent with the principle of prior entry, perception of temporal order was enhanced throughout the period of the AB when T2 was salient, and impaired when T3 was salient. This pattern of results suggests that the effect of salience on the perception of temporal order was broadly additive with the overall AB effect.

5.2. Implications and Future Directions

5.2.1. The AB: The result of one source of delay or many?

In most current accounts, the AB is said to arise from processes or events that occur at a single step in the chain of information processing (e.g., working memory consolidation; Chun & Potter, 1995, Jolicœur & Dell'Acqua, 1998). That is, these theories are predicated on the twin assumptions that processing occurs in sequential stages and that transfer of information from an earlier to a later stage is not possible if the latter is currently busy. In this context, it is tempting to suggest that those processes that were found to be unaffected by the AB in the present work (e.g., those processes indexed by search slope, salience effects) are performed early in the chain of processing events, in an early, preattentive stage of processing, and those processes that were affected by the AB (e.g., those processes indexed by RT, accuracy, perception of temporal order, latency of oddball selection [N2pc]) occur in a later, attentive stage of processing. While possible, this might not necessarily be the case. In fact, the results of the present and related work suggest that, rather than a single bottleneck underlying performance in an AB task, the AB may instead arise from delays or interference at more than one stage of processing.

As discussed in Chapter 3, the substantial differences in the delay in the latency of the N2pc and the RT measures (about 30 ms and 300 ms, respectively) at short compared with long lags may reflect AB-related delays at different stages of processing: deployment of attention to the target in the search display (indexed by the N2pc), and processes that occur after the target has been located, such as extraction of task-relevant information and response planning (included in the RT measure). In other work, we have also shown that accuracy and RT are not always equivalent measures of the AB (Lagroix, Di Lollo, & Spalek, 2015, 2016). Rather, they reflect processes at different levels within the system. We propose that the RT measure is affected by activity at all stages of processing preceding the overt response. Accuracy, on the other hand, encompasses only a subset of those processes subsumed by the RT measure (e.g., attentional selection, identification), but does not reflect the outcomes of other processes (e.g., response planning and execution). We have shown that accuracy and RT measures can reveal qualitatively different patterns of results (i.e., the presence or absence of Lag-1 sparing), suggesting that the AB produces different magnitudes of

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impairments at different levels within the system, consistent with the results of the experiment reported in Chapter 3.

It is possible that some single factor accounts of the AB, such as the "system configuration" factor proposed in the TLC model (Di Lollo et al., 2005) or the locus coeruleus-norepinephrine explanation of Nieuwenhuis, Gilzenrat, Holmes and Cohen (2005), may be able to account for these results by proposing that these single factors have different effects at different levels throughout the system. These results are more difficult to explain, however, using single-factor theories, such as Chun and Potter's two-stage model which propose that the AB arises from a bottleneck located at a fixed stage in a processing hierarchy. For example, theories which place the AB bottleneck at the level of working memory encoding (e.g., Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998) would have difficulties explaining the delay in the latency of the N2pc observed in Chapter 3, since the N2pc is thought to index a selection process that precedes working memory encoding.

5.2.2. Can GS4 Account for the Results reported in Chapters 2-4?

In Chapter 2, we noted that the GS4 model of visual search (Wolfe, 2007) was capable of accounting for the joint findings that (a) the efficiency of pop-out search is not impaired during the period of the AB, and that (b) the level of performance suffers during that period. On the GS4 account, search efficiency is not affected during the period of the AB because the search is performed in the selection bottleneck, which precedes the AB bottleneck (Figure 2.6). As such, search efficiency may be influenced by factors inherent in the selection bottleneck, but not by factors inherent in the AB bottleneck. Once the selection bottleneck has been cleared, target consolidation depends on the state of the AB bottleneck which, in turn, depends on inter-target lag. At long lags, the bottleneck is clear, and the target is consolidated without delay. When lag is short, however, consolidation is delayed in the bottleneck, with consequent slowing of RT. An AB deficit in level of performance then follows.

While providing a rather straightforward account of the results of Chapter 2, the ability of GS4 to account for the results presented in Chapters 3 and 4 is less clear. First, if the N2pc is to be regarded as an index of the attentional selection completed in the selection bottleneck of GS4, it is not clear why the N2pc would be delayed during the

period of the AB, as in the results of Chapter 3, given that the selection bottleneck precedes the AB bottleneck in the GS4 architecture. The increased latency of the N2pc during the period of the AB could be explained, however, on the twin assumptions that (a) top-down guidance of attentional selection processes are impaired during the period of the AB, and that (b) top-down guidance facilitates the speed of the attentional selection indexed by the N2pc. The evidence for these two conjectures is reviewed in the following sections.

Is Top-Down Guidance Impaired during the Period of the AB?

The idea that top-down guidance might be disrupted during the period of the AB seems to be implied in the schematic diagram of GS4 (Figure 2.6). The arrow that represents top-down, re-entrant processing, seems to emanate from the AB bottleneck (Figure 2.6), although this is not explicitly stated. The idea that processes like top-down guidance are impaired during the period of the AB is also consistent with the TLC account of the AB (Di Lollo et al., 2005). According to the TLC model, target selection is governed by an input filter configured endogenously to pass targets and reject distractors. A central processor is charged with both actively maintaining this input filter (by issuing repeated signals to the filter) and encoding targets into working memory. Critically, the central processor can execute only one of these operations at a time. During the period of the AB, the central processor switches from issuing maintenance signals to coordinating the processing of T1. In the absence of maintenance signals, the filter becomes vulnerable to exogenous disruption by stimuli (e.g., distractors) which do not match the filter's current configuration. In this manner, filter configuration – which could be regarded as akin to top-down guidance – is disrupted during the period of the AB.

The empirical evidence for the loss of endogenous control during the period of the AB is rather mixed. Ghorashi et al. (2009, Experiment 2) presented an endogenous cue, indicating the location of the target in a T2 search array, at varying lags throughout the period of the AB. Participants were instructed to attend to the location in the search array opposite to where a peripherally presented cue appeared. The magnitude of the cueing effect was found to be invariant with lag, suggesting that endogenous cueing was equally effective throughout the period of the AB. There are reasons, however, to question the interpretation of these results. First, in this study, the cue appeared only 90

ms prior to the appearance of the target. Endogenous cueing is thought to require a cue-target-onset-asynchrony (CTOA) of at least 150 ms to be effective (Cheal & Lyon, 1991; Jonides, 1981, Müller & Rabbitt, 1989). Second, the dependent measure was the critical exposure duration of the T2 search display, the values of which were very long (about 400-700 ms). The long duration for which the search array remained on the screen leaves open the possibility that participants may have adopted a strategy of completing the processing of T1 and then searching the T2 search array which remained on view. Thus, performance of the search task and the use of the endogenous cue may always have been performed under conditions of full attention regardless of lag, rather than throughout the period of the AB. These are the same considerations that we suggested might underlie performance in the Ghorashi et al. (2007) study. This postponement hypothesis was confirmed in Chapter 2 in which we compared trials in which display duration (short or long) was mixed or blocked. When display duration was blocked and long, participants postponed their search when T2 was presented during the period of the AB (i.e., at short lags). This suggests that it is a very real possibility that the endogenous cueing effects obtained by Ghorashi et al. (2009) were all obtained under conditions when attention was fully available, rather than throughout the period of the AB.

Zhang, Shao, Nieuwenstein, and Zhou (2008) and Zhang, Shao, Zhou, and Martens (2010) have also shown that endogenous cueing, elicited by a centrally presented predictive arrow cue, is invariant with the AB. These results appear more convincing than those of Ghorashi et al. (2009) because these cueing effects were observed with longer CTOAs (180-282 ms) and brief T2 durations (<53 ms). The practice of using arrow cues to direct attention endogenously, however, is not entirely unambiguous. For example, Ristic, Friesen, and Kingstone (2002) have identified an exogenous component in arrow cues, thus questioning the validity of arrow cues as unambiguous elicitors of endogenous processing.

Du and Abrams (2010) also examined the effect of endogenous cueing throughout the period of the AB, but came to the opposite conclusion. That is, they found the effect of endogenous cueing to be reduced during the period of the AB. In their experiments, the cue indicating the location of the T2 target was either the T1 stimulus (the letter L or R, indicating T2 would appear in the left or right position) or was presented before the beginning of the trial, such that participants had time to interpret

the cue and plan their orienting before the AB was induced by the appearance of T1. These results strongly suggest that endogenous control over the ability to orient attention is impaired during the period of the AB. Evidence that endogenous control might be disrupted during the period of the AB is also suggested by recent results showing that the P_D, an ERP component thought to reflect an endogenously controlled suppressive mechanism (Hickey et al., 2009, Hilimire, Hickey, & Corballis, 2012) is absent during the period of the AB (Gaspar, 2016; McDonald, Gaspar, Lagroix, & Di Lollo, 2014).

The idea that endogenous control is lost during the period of the AB also seems consistent with the results of Experiment 2 in Chapter 4. The interaction of salience and lag suggests that endogenous salience was slightly impaired during the period of the AB, although the effects of salience and of lag were broadly additive (see Figure 4.4B). It should be noted that the effect of our exogenous salience manipulation in Experiment 1 of Chapter 4 was also impaired during the period of the AB (Figure 4.3B). This manipulation, however, may not have been purely exogenous. The advanced knowledge of the colour of the "exogenously" salient stimulus (red) in Experiment 1, might have introduced an endogenous component to this salience manipulation. It is possible that it is this endogenous component which was slightly impaired during the period of the AB, while the exogenous component was entirely unaffected. These considerations would bring the results of Chapter 4 in line with predictions based on the interpretation that, according to GS4, top-down (endogenous) guidance is impaired during the period of the AB, but bottom-up (exogenous) guidance is unaffected

On this proposal, it could be suggested that top-down guidance was also impaired during the period of the AB in the experiments reported in Chapter 2. Any such loss of top-down guidance, however, did not impair the efficiency of search. On this view, the bottom-up guidance, which is unaffected by the availability of attention, must have been sufficient to support efficient pop-out search throughout the period of the AB.

Does Top-Down Guidance Modulate the Latency of the N2pc?

On the hypothesis, outlined above, that (a) the attentional selection mechanism indexed by the N2pc corresponds to the selection bottleneck in GS4, and that (b) top-down guidance is impaired during the period of the AB, the delay in the latency of the N2pc observed in Chapter 3 would need to be accounted for by an impairment in top-

down guidance. There is strong evidence to suggest that the N2pc is affected by top-down attentional set. For example, Kiss, Jolicœur, Dell'Acqua, and Eimer (2008) showed that the amplitude of the N2pc was modulated by task instructions, rather than purely by bottom-up salience (see Theeuwes, 1991, 1994). This general effect, that top-down factors modulate the N2pc, has also been observed in a number of other studies (e.g., Eimer & Kiss, 2008; Eimer, Kiss, Press, & Sauter, 2009; Kiss, Driver, & Eimer, 2009; Leblanc, Prime, & Jolicœur, 2008; Lien, Ruthruff, Goodin, & Remington, 2008). This is not to say that the attentional selection indexed by the N2pc is not also strongly affected by bottom-up salience (e.g., Hickey, McDonald, & Theeuwes, 2006). Rather, these results indicate that top-down factors do play a role in the attentional selection indexed by the N2pc.

While most of these results demonstrate that the amplitude of the N2pc is modulated by top-down factors, there is also evidence to suggest that top-down guidance can facilitate the latency of the N2pc. Grubert and Eimer (2013) found N2pc components to be delayed when participants had to search for multiple possible target colours relative to a single possible target colour. Kiss et al. (2009) also showed that the latency (as well as the amplitude) of the N2pc was modulated by reward priorities. That is, the N2pc component emerged earlier, and with a larger amplitude, when the target was associated with a high, relative to a low, reward. These results suggest that stronger top-down guidance results in faster attentional selection and would be consistent with our proposal that the delay in the onset latency of the N2pc observed in Chapter 3 may be due to impairments in top-down guidance during the period of the AB.

In conclusion, if top-down guidance of attentional selection is assumed to be impaired during the period of the AB, the GS4 model appears to be able to account for the various results reported in Chapters 2 to 4.

5.2.3. Additional Suggestions for Future Research

Comparing the Results in Chapter 2 with Earlier Results

The finding in Chapter 2 that the efficiency of pop-out search was not impaired while attention was less available during the period of the AB seems to be consistent with some findings in the literature (e.g., Braun & Sagi, 1990; Braun & Julesz, 1998), but inconsistent with others (e.g., Belopolsky, & Theeuwes, 2010; Di Lollo, Kawahara, Zuvic,

& Visser, 2001). Some reasons why the present results are inconsistent with the findings of Di Lollo et al. (2001) and Belopolsky and Theeues (2010) are discussed below.

Di Lollo et al. (2001) completed a series of five experiments which suggested that search efficiency is determined by the appropriateness of the configuration of the system for completing a search task. In Experiments 3 and 4, they demonstrated that search was inefficient (slopes were steep) if the search task was preceded by the requirement to perform an unrelated task (determining whether the top and bottom lines of a hexagonal frame surrounding the search array were tilted in the same direction). If, however, the displays and tasks remained the same but their order was reversed such that the search task was completed first, search was found to be efficient (slopes were flat). This pattern of results prompted the conclusion that search can be performed efficiently only if the system is suitably configured for the task. If the system is not configured appropriately as when an unrelated task precedes the search task, inefficient search slopes are observed.

Based on these findings, I would have expected that in the experiments reported in Chapter 2 search should have been inefficient during the period of the AB, while the system was configured for T1 processing rather than for performing the T2 search task. Instead, we found search to be efficient throughout the period of the AB, suggesting that system configuration did not affect search efficiency. The reason why search efficiency was not impaired under dual-task conditions in the present work, but was impaired in the experiments reported by Di Lollo et al. (2001), remains unclear.

There are several procedural differences between the experiments which may have influenced the results (e.g., the spatial configuration of the search displays, range of set sizes, the dependent measures [critical ISI vs RT], the presence/absence of a masking stimulus). Most notably, in Di Lollo et al.'s (2001) experiments, the stimuli on which the two tasks were performed were displayed simultaneously, whereas in the present work, they appeared sequentially. It is possible that the system configuration effects observed by Di Lollo et al. are quite short lived, such that the system was already suitably configured for the search task by the time the search array appeared only 100 ms later at the shortest lag in the experiments reported in Chapter 2. However, this proposal is not consistent with theories of the AB, like TLC (Di Lollo et al., 2005), which argue that system configuration is impaired throughout the period of the AB (i.e., for

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about 500 ms), while processing of T1 is ongoing. Systematic investigations will be required in order to determine which factors underlie the different results.

The search efficiency results reported in Chapter 2 also appear to be inconsistent with the findings of Belopolsky and Theeuwes (2010, Experiment 2). In their Experiment 2, participants had to monitor either a RSVP or a rapid serial auditory presentation (RSAP) stream of letters for the letter "K". Both the RSVP and RASP streams were presented simultaneously in all conditions. Only on trials in which a "K" was present (Go Trials) in the relevant stream were observers to search a circular array of shapes, presented visually, around the RSVP stream, for a shape singleton. The search array appeared simultaneously with the letter "K" (or a non-K letter, on No-Go trials). The task was to report the orientation of the line (vertical or horizontal) presented within the shape singleton. An irrelevant colour singleton was also present in the display on half of the trials.

Belopolsky and Theeuwes (2010) called the condition in which participants were instructed to monitor the RSVP stream for the letter "K" the *focused* attentional window condition because they theorized that this task would require that their "spatial attentional window" (see Belopolsky, Zwaan, Theeuwes, & Kramer, 2007; Theeuwes, 1994, 2004) be focused narrowly in order to monitor the RSVP stream. By contrast, they called the condition in which participants were instructed to monitor the RSAP stream, the *diffuse* attentional window condition because visual attention did not need to be focused narrowly on the RSVP stream. In the focused condition, search was less efficient than in the diffuse condition. This prompted the authors to conclude that "When attentional window is wide all items are processed in parallel across the visual field and all salient elements capture attention irrespective of a top-down goal. However, when attentional window is small search becomes less efficient, even in a classic pop-out search task." (p.2549). That is, the authors argue (see also Theeuwes, 2010) that the salience computations which underlie efficient visual search occur only within the attentional window. Therefore, if a search array appears outside of the current focus of the attentional window, the efficiency of search will be impaired.

On this attentional window theory, search efficiency should have been impaired in the experiments reported in Chapter 2 because participants were required to monitor an RSVP stream for a target letter, much as in the focused condition of Belopolsky and

Theeuwes (2010). It is possible, however, that the successive target displays employed in the experiments reported in Chapter 2 permitted attention to become diffuse by the time the T2 search array appeared, as soon as 100 ms after T1. This possibility is inconsistent, however, with existing findings that demonstrate that rather than attention becoming more diffuse upon the presentation of T1, attention actually seems to contract reflexively onto the location of T1 for at least the first 150 ms after T1 appears, so as to optimize its processing (e.g., Jefferies & Di Lollo, 2009; Jefferies, Ghorashi, Kawahara, & Di Lollo, 2007; Visser, Bischof, & Di Lollo, 2004).

The attentional window account would also appear to have difficulties accounting for the results of Di Lollo et al. (2001) in which search efficiency was shown to be impaired when it was performed after an unrelated frame task. The frame task involved determining whether the top and bottom lines of a hexagonal frame surrounding the search array were tilted in the same direction. Critically, since the frame was presented surrounding the search array and the task involved comparing the tilt of two lines presented on opposite sides of the search array, one would think that observers would have adopted a diffuse attentional window that would have at least encompassed the frame and the search array contained within it. On the attentional window hypothesis, this diffuse attentional window configuration should have yielded efficient search slopes, rather than the inefficient slopes observed by Di Lollo et al. (2001). It is possible however, that attention was narrowed to each side of the frame in succession, such that it did not encompass the search array, thereby causing search to be inefficient. These possibilities would need to be explored empirically.

In addition, I would argue that Di Lollo et al.'s (2001) system configuration account of search efficiency cannot fully account for the outcomes of Belopolsky and Theeuwes' (2010) Experiment 2. In both the focused and the diffuse conditions, the participants had to perform a letter discrimination task (K or not-K) before they could perform the search task. On the system configuration hypothesis, in both conditions, the system should have been configured to complete the letter discrimination task rather than being configured for the search task, and, therefore, inefficient search slopes should have been obtained in both conditions, rather than only in the focused condition. Perhaps the system configuration hypothesis could account for this finding by suggesting that separate configurations can be maintained in the auditory and visual

modalities, which would have allowed the system to be optimally configured in the diffuse condition in which efficient search slopes were obtained.

In summary, it appears as though neither the system configuration, nor the attentional window theory can account for all of the findings discussed in this section (Chapter 2; Belopolsky & Theeuwes, 2010; Di Lollo et al, 2001). Further investigations will be required in order to determine which factors are responsible for the search efficiency effects.

Ppc as an Index of Salience and Search Efficiency

Some recent studies have demonstrated that the Ppc (positivity posterior contralateral) ERP component is unimpaired during the period of the AB (Corriveau, Fortier-Gauthier, Pomerleau, McDonald, Dell'Acqua, & Jolicoeur, 2012; Gaspar, 2016; Pomerleau, Fortier-Gauthier, Corriveau, McDonald, Dell'Acqua, Jolicœur, 2014). It has been suggested that this component may reflect the preattentive activation of the location of a salient item in a salience map (e.g., Corriveau et al., 2012; Fortier-Gauthier, Dell'Acqua, & Jolicœur, 2013; Jannati, Gaspar, & McDonald, 2013). This idea that salient items are represented preattentively in salience maps is consistent with some theories of visual search (e.g., Treisman & Gelade, 1980; Wolfe, 2007). On this salience hypothesis of the Ppc, the finding that this component is invariant with the AB would be consistent with the results of Chapters 2 and 4 in the present work, which suggest that salience is relatively unimpaired during the period of the AB.

Jannati, Gaspar, and McDonald (2013) compared the amplitude of the Ppc on fast and slow search trials, and found the Ppc to be invariant with RT. This outcome prompted the conclusion that "the Ppc was not related to the efficiency of search or target processing" (Jannati, Gaspar, & McDonald, 2013, p.10). The index of search efficiency in this work, however, was the overall level of RTs, rather than the slope of the search function over set sizes, as in the present work. As demonstrated in Chapter 2, the overall level of RT need not correspond to the slope of the search functions over set size. That is, search slopes can be efficient both when RTs are slow and fast. It may, therefore, be interesting to follow-up this work by examining the correspondence of the Ppc with search efficiency. If the Ppc represents a salience signal, and salience determines search efficiency, the Ppc should be weaker under conditions in which search efficiency is impaired (e.g., when target salience is low because target-distractor

similarity is high; Duncan & Humphreys, 1989). These investigations may help elucidate the processes underlying both visual search and the Ppc.

5.2.4. Concluding Remarks

There are two main conclusions that can be drawn from the work described in this thesis. The first pertains to the concept of bottleneck in the chain of information processing events. Contrary to the widespread notion of a single AB bottleneck, the compelling message from the present experiments is that processing can be delayed at several junctures (e.g., attentional selection, transfer into working memory, response planning and execution). The second pertains to the classification of visual search as preattentive or attentive. As noted above, the question of whether visual search can be performed without the involvement of attention is ill-posed. What needs to be specified is what aspects of the search task are influenced by processes commonly denoted by the rubric "attention".

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