MASKING IN THE ATTENTIONAL BLINK: IMPLICATIONS FOR A PRECONSCIOUS MEMORY BUFFER

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ABSTRACT

In the attentional blink (AB) perception of the second of two visual targets (T2) is impaired if presented within about 500ms of the first (T1). We adopted the hypothesis that, during that period, a representation of T2 is stored in a preconscious buffer (PCB) while T1 is processed. We studied the characteristics of the PCB by asking what types of visual masking interfere with the stored memory representation. We investigated three masking procedures: delayed pattern masking, delayed metacontrast, and common-onset metacontrast masking. Delayed masks trigger onset transients in low-level vision, whereas common-onset masks involve mainly higher-level visual areas. The results showed that the AB occurred with all three procedures, strongly suggesting that neither overlap of contours between target and mask nor unique onset transients triggered by the trailing mask are necessary to produce an AB deficit. We conclude that the most likely locus of the PCB is in high-level vision.

Keywords: attentional blink; preconscious buffer; pattern masking; metacontrast masking; common-onset masking; object-substitution masking.

Subject Terms: Attention; Cognition; Cognitive neuroscience; Consciousness; Perception; Visual masking.

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1: INTRODUCTION

1.1 The attentional blink paradigm

When a sequence of visual stimuli consisting of several distractors and two targets are presented one at a time in rapid succession at the same spatial location (RSVP: rapid serial visual presentation), if participants detect the first target (T1), they will often fail to detect the second target (T2), if it is presented within ~ 200-500 ms after the first one. This phenomenon is called attentional blink (AB; Raymond, Shapiro, & Arnell, 1992). The term “Lag” refers to the position of T2 relative to T1, e.g. Lag 1 refers to the condition in which T2 comes directly after T1, and Lag 3 means that T2 is the third item after T1 with two intervening distractors. Usually, the AB is most prominent at Lags 2 or 3 where the subjects report T2 correctly with the lowest probability.

Why is the AB worth studying? Any practical value that the AB might have in the real world is surpassed by its potential as a tool for studying how the mind works and how it is implemented in the brain. Theories of the AB can be regarded as guesses about the brain mechanisms that cause perception of T2 to be impaired when it is presented shortly after T1. Here, we claim that current theories have fallen short of that objective because they have not addressed the critical issue. This claim is based on two main findings that have emerged from the AB literature:

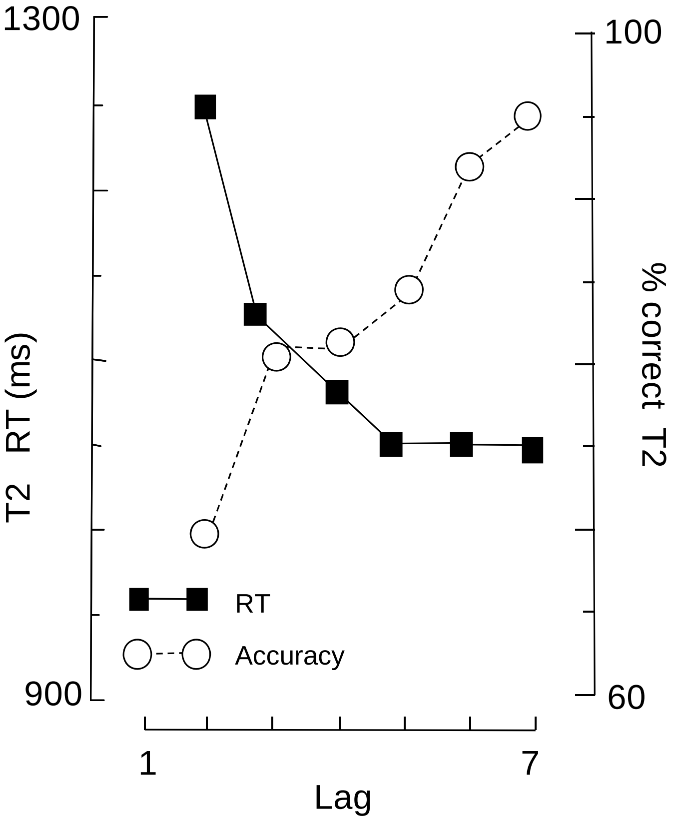
[a] correct reporting of T2 is delayed over a brief period following the presentation of T1.

[b] the internal representation of T2 is vulnerable to masking during the period of delay.

The finding in [a] is well-documented (e.g., Ghorashi, Smilek, & Di Lollo, 2007; Jolicœur & Dell'Acqua, 1998; Kawahara, Di Lollo, & Enns, 2001; Vogel, Luck, Shapiro, 1998). Di Lollo, Kawahara, and Spalek (personal communication, May, 2009) built on that finding in a pilot study in which they recorded both accuracy and reaction time (RT) to T2. The targets were two letters inserted in a stream of digit distractors presented in rapid serial visual presentation (RSVP). T2 was always followed by a distractor that acted as a mask. The results (Fig. 1) revealed a substantial AB deficit in accuracy, and progressively decreasing RTs as the T1-T2 lag was increased. Vogel et al. (1998) reported similar results for the latency of the P300 component of the event-related potential (ERP). Also, Vogel & Luck (2002) reported that when an unmasked T2 was presented at Lag 3, the onset latency of the P300 wave of the ERP was delayed by over 100 ms relative to Lag 7. Collectively, the RT and ERP results strongly suggest that processing of T2 is delayed as a consequence of the system attending to T1.

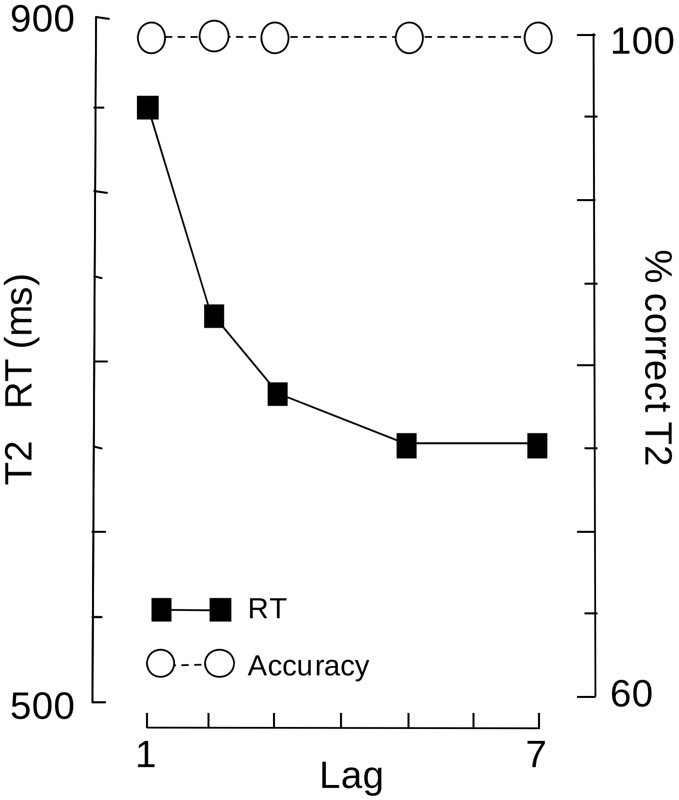
The finding in [b] is also well-documented (e.g., Giesbrecht & Di Lollo, 1998). Di Lollo et al. (personal communication, 2009) pursued it in a pilot study similar to that illustrated in Fig. 1, with the notable exception that T2 was never followed by a mask (i.e., T2 was the last item in the RSVP stream). The results (Fig. 2) revealed no AB deficit in accuracy. In contrast, RT decreased progressively as lag was increased, much as when T2 was followed by a mask (Fig. 1).

Figure 1. **Mean percentages of T2|T1 correct responses and T2 reaction times as a function of Lag when T2 was followed by a mask (Di Lollo, Kawahara, & Spalek, personal communication, 2009).**



It must be emphasized that the absence of an AB in accuracy was not due to the fact that T2 performance was at ceiling (Fig. 2). Giesbrecht and Di Lollo (1998) have shown that when T2 is not followed by a mask, no AB deficit is in evidence even when performance is brought well below ceiling by degrading T2. In brief, the evidence strongly suggests that the processing of T2 is delayed whether or not T2 is followed by a mask. In contrast, an AB deficit in accuracy hinges on T2 being masked.

Figure 2. Mean percentages of T2|T1 correct responses and T2 reaction times as a function of Lag when T2 was not followed by a mask (Di Lollo, Kawahara, & Spalek, personal communication, 2009).



In light of these results, we can pose the key question: What is the root cause of the AB? It cannot be the delay in T2 processing, as such, because no AB deficit in accuracy occurs even when processing of T2 is delayed, provided that T2 is not masked (Fig. 2). Similarly, it cannot be masking, as such, because, at long lags, accuracy for T2 is high despite the presence of a trailing mask (Fig. 1, Lag 7). This pattern of results is in keeping with the hypothesis that *the root cause of the AB is backward-masking of T2 during the period of delay following* *the presentation of T1*. From this perspective, the AB is seen not as a primary phenomenon but as a derivative effect arising from the conflation of two separate factors that can be – and have been – studied independently: delayed responding to the second of two targets (Psychological Refractory Period; PRP; e.g., Telford, 1931) and backward masking (e.g., Breitmeyer, 1984). It is perhaps worth noting that the phenomenon known as “Lag-1 sparing”, high T2 performance at Lag 1, may require separate consideration.

To be sure, the above hypothesis is not entirely new. It forms part of two prominent models of the AB: the two-stage model (Chun & Potter, 1995) and the bottleneck model (Jolicœur & Dell'Acqua, 1998). Both these models, as well as other models, acknowledge the importance of the two findings in [a] and [b] above. However, while proffering hypotheses as to the cause(s) of the delay, no extant model has anything to say about the masking of T2, other than to acknowledge its necessity. To be clear about this, masking of T2 is not part of the conceptual framework of any current model of the AB. Instead, the current models are accounts of the delay in processing T2, namely, the PRP. However, we have seen that a delay, as such, does not lead to an AB deficit (Fig. 2). These theories, therefore, must be regarded as incomplete because they purport to account for the delay but not for why the AB depends critically on masking during the delay. What these theories do not explain is why T2 is vulnerable to masking only during the delay, not outside it.

1.2 Preconscious buffer

Behavioural, electrophysiological, and imaging studies have suggested that stimuli that fail to be explicitly reported during the AB are nevertheless registered in the brain (e.g., Luck, Vogel, & Shapiro, 1996; Marois, Yi, & Chun, 2004; Shapiro, Driver, Ward, & Sorensen, 1997). Therefore, it can be inferred that during the period of delay in the processing of T2, its representation must be stored in a temporary buffer until attention can be deployed to it, and its processing can be completed. While stored in the buffer, the representation may be encoded in such a way as to be vulnerable to masking by the trailing item and to decay.

Suppose that, while delayed, the internal representation of T2 is stored in a short-lived memory buffer. That buffer is unlikely to be the same as working memory for several reasons. Its duration is limited to a few hundred ms (i.e., the period of the AB), as distinct from several seconds. Unlike working memory, its contents are not available for rehearsal or for conscious awareness. Rather, the buffer may be related to the type of memory known as *iconic memory* (Coltheart, 1980; Di Lollo, 1980; Sperling, 1960).

It is also plausible that the labile memory buffer in which the T2 representation is stored while the system is busy processing T1 may correspond to a '*preconscious'* stage of processing described recently by Dehaene, Changeux, Naccache, Sackur, & Sergent (2006). They conceptualized preconscious processing as a form of non-conscious processing in which neural activation can be intense, durable, and can spread to several specialized sensorimotor areas (e.g. frontal eye fields). However, when top-down attention is oriented away from the stimulus, activation cannot access higher parieto-frontal areas. Therefore, such activation cannot establish long-distance synchrony and be maintained in working memory, and, subsequently, is not capable of guiding intentional actions including verbal reports. Critically, preconscious processing potentially carries enough activation for conscious access but is temporarily buffered in a non-conscious store because of lack of top-down attentional amplification (Dehaene et al., 2006). In other words, preconscious processing results in maintaining the representation of the stimulus temporarily active for a few hundred milliseconds in a buffer that is not consciously accessed at the moment, but which is potentially accessible upon being attended. We refer to this buffer as *preconscious buffer* (PCB).

The main objective of the present work is to use the AB deficit as a tool of convenience to study the characteristics of the PCB. A basic initial question in defining those characteristics is to ask what types of masks can interfere with its contents. Not surprisingly, given the current theoretical perspective on the AB, no systematic work on this issue is to be found in the literature. For example, it is not clear whether an AB occurs when T2 is backward-masked by metacontrast rather than by the conventional pattern masks. In the following sections, we first describe the characteristics of pattern and metacontrast masking, and then we explain how studying the effects of these types of masking in the AB paradigm can aid in discovering the properties of the PCB.

1.3 Different types of visual masking

Two main types of visual masking have been studied in the literature: a) ‘pattern masking’ that occurs when perception of a target is impaired by a temporally trailing, spatially overlapping, stimulus consisting of a field of noise or structured contours, and b) ‘metacontrast masking’ in which the contours of the mask are adjacent to – but do not overlap with – the contours of the target (Breitmeyer, 1984).

1.3.1 Pattern masking

The masking literature indicates that pattern masking is mediated by two major processes: *integration* of contours and *interruption* of processing (Scheerer, 1973; Spencer & Shuntich, 1970). Integration occurs when target and mask are combined into a unitary percept as a consequence of imprecise temporal resolution in the visual system, resulting in degradation of the image of the target by the superimposed contents of the mask. In this case, masking is akin to the addition of spatial noise (the mask) to the signal (the target) at early levels of visual processing and, therefore, is referred to as ‘integration masking’ (Breitmeyer, 1984; Kahneman, 1968; Scheerer, 1973). The temporal function of this type of masking is approximate symmetry around a peak at a stimulus-onset asynchrony (SOA, the interval from the onset of the target to the onset of the mask) of zero, i.e., simultaneous presentation of the target and mask. As the SOA is increased, the strength of integration is diminished with a complete absence of masking beyond an SOA of about 100 ms (e.g., Di Lollo, 1980).

‘Interruption masking’ occurs when processing of the target is disrupted by a mask that appears in the same spatial location before the target has been fully processed. Instead of involving the early stages of processing, where contours are defined, interruption masking involves a competition for higher-level mechanisms that are responsible for object recognition (Kolers, 1968). In other words, the high-level processing mechanisms that are required in common by both stimuli are taken over by the mask. Therefore, unlike integration, the process of interruption does not degrade the target; rather, the processing of the target is cut short by the onset of the mask (Di Lollo, Enns, & Rensink, 2000; Michaels & Turvey, 1979; Scheerer, 1973; Turvey, 1973). As a result, the amount of time available for processing the target is sharply curtailed if a mask follows in rapid succession. The interruption masking function is referred to as U- or J-shaped because target accuracy is often lowest at SOAs that are greater than zero and improve at longer SOAs (e.g. Bachmann & Allik, 1976; Purcell & Stewart, 1970).

According to the two-factor theory of Spencer and Shuntich (1970), backward masking by pattern with SOAs up to ~ 100 ms is due to integration and consequent target degradation. At longer SOAs, however, the pattern mask produces its effect by interrupting target processing. Besides differing in temporal characteristics, integration and interruption masking can be distinguished based on physical attributes (e.g., target and mask luminance and contrast) and informational attributes (e.g. processing load or set size). The physical attributes exclusively influence integration masking, e.g., integration increases with the luminance contrast of the mask (Breitmeyer, 1984; Scheerer, 1973; Spencer & Shuntich, 1970). However, informational attributes mainly influence interruption masking, e.g., varying the number of potential targets (i.e. manipulating set size) markedly increases masking by interruption but has little effect on integration masking (Spencer & Shuntich, 1970). Therefore, two distinct limiting conditions determine performance under pattern masking, one of them related to *stimulus energy* (e.g., target and mask luminance, SOA within the limits of time-intensity reciprocity), the other to *stimulus information* (e.g., processing load; Scheerer, 1973). It is conceivable that both aspects contribute to pattern masking under all conditions, and performance will be limited by whatever condition sets the lower limit (i.e., stimulus energy under low-energy conditions, stimulus information under high-information conditions; Scheerer, 1973). This indicates that pattern masks may operate at both low and high levels of visual processing, depending on SOA and other experimental conditions such as those mentioned above.

1.3.2 Metacontrast masking

Metacontrast masking occurs when the shape of the mask closely fits the contours of the target shape but does not overlap with them (Alpern, 1953; Breitmeyer, 1984). When the SOA between the target and the mask is either very short or very long, the target is perceived clearly and accurately. However, at intermediate SOAs, perception of the target is impaired and results in a U-shaped function of accuracy over SOA. Estimates of the optimal SOA for metacontrast masking tend to fall in the range of 50 to 150 ms. Because of its stability, this temporal characteristic has been called the *onset-onset law*

(Kahneman, 1967) or the *SOA law* (Breitmeyer, 1984). The finding that metacontrast masking occurs at relatively short SOAs, compared to pattern masking, and in absence of integration (due to lack of contour superimposition) is consistent with the claim that this type of masking occurs early in the chain of processing events.

One of the mechanisms thought to be involved in metacontrast masking is the inhibitory interaction between neurons representing the contours of the target and the mask (Breitmeyer, 1984; Weisstein, Ozog, & Szoc, 1975). It is believed that the onset of each stimulus triggers neural activity in two channels; one fast-acting but short-lived, the other slower acting but longer lasting. The fast-acting channel transmits transient events that signal stimulus onset and offset, whereas the slower channel carries sustained signals regarding such stimulus attributes as shape and color. Onset transients are brief bursts of firing by neurons in the visual pathway in response to sudden increases in the intensity of retinal stimulation that are large relative to the maintained response (Adrian and Matthews, 1927; Ogawa, Bishop, & Levick, 1966; Phillips and Singer, 1974b; Winters and Walters, 1970). It has been suggested that at least one of the functions of such transient responses is to draw attention to new events thereby facilitating their detection (Phillips and Singer, 1974a; Yantis & Jonides, 1984). In one well-established theory (Two-Channel Theory; Breitmeyer & Ganz, 1976), metacontrast masking occurs when the sustained activity generated by the target is inhibited by the fast-acting signals in response to the trailing mask. Consistent with this theory are the findings on the relationship between masking strength and contour proximity. As the separation between target and masking contours is increased even by a fraction of a degree, masking is sharply reduced (Breitmeyer, 1984; Growney, Weisstein, & Cox, 1977; Kahneman, 1967). Furthermore, unlike masking by pattern, metacontrast masking is critically dependent on stimulus intensity and contrast (Breitmeyer, 1984). The dependence of masking on both contour proximity and stimulus intensity and contrast provides substantial evidence for a low-level masking by metacontrast.

In brief, pattern masking can potentially act at both high and low levels of visual processing, whereas metacontrast masking occurs mostly at low levels in the visual system. Most of the AB studies so far have used pattern masking as the type of backward masking necessary for eliciting an AB deficit. Therefore, such studies, by themselves, cannot indicate the level of information processing required for holding the T2 representation in the PCB, nor can they provide evidence for the locus of the PCB in the visual system. However, demonstrating the ability of metacontrast masking to produce an AB deficit would indicate a low-level locus for the PCB, or at least reveal the role of early visual processing areas in the storage of information in the PCB. Therefore, as a first step, we propose using a taxonomic approach in which T2 is followed by either a pattern mask or a metacontrast mask. The metacontrast mask will be presented either in the RSVP frame following T2 ("delayed mask") or in the same frame as T2, with the mask remaining on view alone for some time after T2 offset ("common-onset mask", Di Lollo et al., 2000).

1.3.3 Common-onset masking

Common-onset masking can best be illustrated by an example. Di Lollo, Bischof, & Dixon (1993) conducted an experiment in which the target was a square outline with a small gap on one of its sides. The target was presented within a slightly larger square mask with a gap on each side. The task was to report the location of the gap in the target. The sequence began with a simultaneous display of both target and mask for a brief period (10 ms). Then the inner target square was turned off, and the outer (masking) square remained on display for durations of up to several seconds (including a duration of 0). The participants were able to identify accurately the location of the gap in the inner square only if the target and the mask both started and ended together. However, if the initial two-square configuration was continued with a display of the masking square alone, target processing was impaired and the gap location could not be reported accurately. This type of backward masking is called ‘common-onset masking’ (COM; Bischof & Di Lollo, 1995; Di Lollo et al., 1993, 2000). It has been shown that the masking efficiency in a COM paradigm increases with the set size or duration of the mask after the target offset (Di Lollo et al., 2000).

COM is a type of backward masking that can be easily distinguished from pattern masking (Breitmeyer, 1984). Although the temporally trailing mask seems to interrupt the target processing, COM cannot be regarded as an instance of interruption masking that is one of the two major processes underlying pattern masking (Di Lollo et al., 2000). This is because: 1) all theories of interruption masking are based on the mask following the target in time, and it is the onset of the mask that interrupts the processing of the target (Breitmeyer, 1984; Michaels & Turvey, 1979; Turvey, 1973). However, in COM, the onsets of the target and the mask are simultaneous and, therefore, there is no mask onset separate from the onset of the target; 2) an essential component of pattern masking is superimposition of the target contours and those of the mask which does not occur in COM; 3) simultaneous beginning of the target and the mask, as in COM, is the defining characteristic of integration, but not interruption, masking (Di Lollo et al., 2000).

COM cannot be considered as a form of metacontrast masking either. A critical difference between the two is that in order for metacontrast masking to be effective, the onset of the target must precede the onset of the mask by some temporal interval (SOA law; Breitmeyer, 1984; Kahneman, 1967). In other words, no metacontrast masking can be achieved at an SOA of zero, provided that the target and the mask terminate together (Breitmeyer & Ganz, 1976; Weisstein et al., 1975). Current theories of metacontrast masking depend critically on the SOA law and consider metacontrast as an effect based on transient neural responses triggered by the onsets of the stimuli. In particular, inhibitory models including the Two-Channel theory cannot account for COM because they are based on the interaction between excitatory and inhibitory processes that cannot occur appropriately when the target and the mask are presented simultaneously (Alpern, 1953; Breitmeyer & Ganz, 1976; Matin, 1975; Weisstein et al., 1975).

In COM, the emerging representation of a target is replaced by the emerging representation of a trailing mask as the object in a given spatial location. This process has been referred to as *‘object substitution masking’* (OSM; Enns, & Di Lollo, 1997). OSM can be distinguished in two ways from types of masking in which low-level factors play a critical role: 1) it is largely insensitive to contour proximity and stimulus luminance; 2) it is strongest when visual attention is misdirected or spatially distributed in the visual field. The term ‘object-substitution masking’ refers to these two critical aspects of COM (Di Lollo et al., 2000; Enns, & Di Lollo, 1997).

One major theoretical account used to explain COM is based on iterative re-entrant processing. According to Di Lollo et al. (2000), the onset of the display triggers low-level activity in the visual system and leads to the formation of tentative representations at higher levels. Such representations require verifications for several reasons such as their multiplicity, ambiguity or being ill-defined. Reentrant comparisons between the high-level representations and the ongoing low-level activity produced by the initial stimulus can resolve these issues. During such iterative reentrant activity, specific visual features are bound with the appropriate objects in the visual environment.

However, in an COM paradigm, the target is turned off before its processing is complete, and the mask continues to be present in the location previously occupied by both the target and the mask. The ongoing low-level activity, consisting of a decaying image of the target and an undiminished image of the mask, creates an ambiguity that interferes with the target identification process. Over successive iterations, the correspondence between this ongoing activity and the initial reentrant signal (target + mask) decreases. At the same time, the continued presence of the mask maintains a strong low-level activity whose correspondence with the current reentrant signal (mask alone) increases. Therefore, as the duration of the trailing mask is increased, the probability of the (target + mask) high-level code being replaced by the (mask alone) code increases and at long-enough mask durations, only the mask is perceived (Di Lollo et al., 2000).

Although it has been noted that the findings from conventional pattern and metacontrast masking are consistent with the pattern of results observed in COM (Di Lollo et al., 2000), common-onset masks differ critically from delayed masks in that they do not trigger onset transient separately from the target. In a delayed masking paradigm, the onset transient responses triggered by the sudden onset of the mask can inhibit the ongoing sustained response to the immediately preceding target, thereby impairing target identification (e.g., Breitmeyer & Ganz, 1976). However, since in the COM paradigm, the target and the mask are presented simultaneously, such onset transient events are not produced uniquely by the mask but by a combination of the target and the mask, and, therefore, cannot influence the strength of masking.

1.4 Objectives

Based on the characteristics of pattern, metacontrast, and common-onset masking described above, comparing the effects of these types of visual masking in an AB paradigm allows for an examination ot the following issues in regard to the PCB: 1) the effects of contour superimposition, contour proximity and object substitution; 2) the necessity of onset transients for interfering with the contents of the PCB; and 3) the high- vs. low-level locus for the PCB in the visual system. To be useful for the objectives of this research, the masks must meet an obvious criterion: they must be effective only during the period of the AB, not outside it. Otherwise, the masking effects cannot be necessarily assumed to be interfering with the PCB *per se* but with any step in the chain of processing events from early subliminal to conscious processing of the target stimuli.

2: EXPERIMENT 1

Experiment 1 was designed to find out whether pattern and metacontrast masking differ in the degree to which they interfere with the information in the PCB. Specifically, the objective was to learn whether superimposition of contours was necessary for masking T2 during the period of the AB. Given that metacontrast masking occurs at early stages of processing in low-level vision, and that pattern masking can occur at both low and high levels, Experiment 1 will also provide evidence regarding the locus of the PCB within the visual system.

2.1 Method

2.1.1 Participants

Fifteen undergraduate students participated for course credit. All reported normal or corrected-to-normal vision and were naive to the purpose of the experiment. All gave written informed consent prior to the experiment. The Office of Research Ethics at Simon Fraser University approved this study.

2.1.2 Apparatus and stimuli

The experiment was run in a dimly lit room. Participants sat at a distance of approximately 60 cm from the monitor. They viewed an RSVP stream that included black digit distractors and two target letters (48-point Geneva font) in the centre of the screen against a white background. Each item in the RSVP stream remained on the screen for 50 ms, and there was a white blank screen for 50 ms between successive items, yielding a presentation rate of 10 items/sec. The RSVP stream contained a variable number of digit distractors and two letter targets, selected randomly, from the English alphabet, except I, O, Q, and Z. The number of distractors preceding the first target (T1) was determined randomly on each trial and varied between 5 and 10, inclusive. On any given trial, the distractors were selected randomly, with replacement, from the set of digits 0–9, with the constraint that the selected digit was not one of the two preceding items.

The second target (T2) was then presented at one of three lags after the first target: 100, 300, or 700 ms, i.e. Lags 1, 3 and 7, respectively. The lag was selected randomly for each trial, with the constraint that there was an equal number of trials per lag in each block of trials. Digit distractors continued to be presented during the inter-target interval. T2 was then presented for 50 ms, followed by a 50-ms white blank interval. Then the masking display (pattern or metacontrast) appeared which remained on the screen for 50ms. The pattern mask was a digit selected randomly from the set of digits 0-9 with the constraint that the selected digit was not the same as the distractor preceding T2. The metacontrast mask was a black square (1.2º × 1.2º), which was presented in the centre of the screen. The mask had the same line thickness as the target letters and if T2 and the metacontrast mask were presented together, the maximum separation between the two would never be more than approximately 4-min of visual angle.

2.1.3 Design and procedure

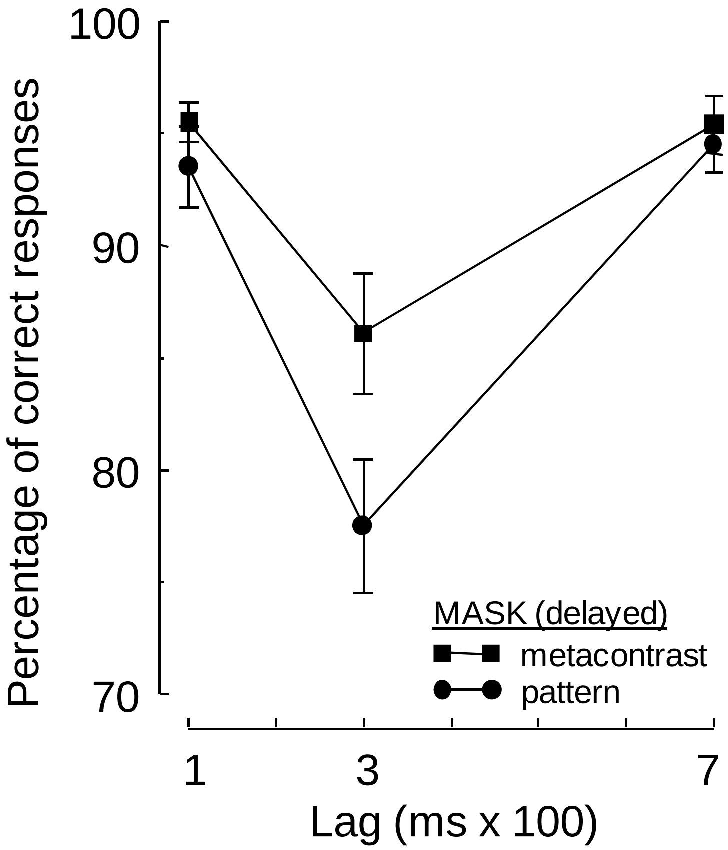
The experiment comprised two blocks of trials: pattern masking and metacontrast masking. The order of the two blocks was counter-balanced among the participants. At the beginning of each trial, a small fixation cross was presented in the center of the screen. Participants initiated each trial by pressing the space bar. They were required to ignore the distractors and to report the identity of T1 and T2, one at a time and at their leisure by pressing the corresponding keys on the keyboard upon being prompted.

Participants were given 10 practice trials at the beginning of each session. These were followed by a total of 240 trials, 120 for each block, and 40 for each of the three lags.

2.2 Results and discussion

The mean T2 accuracy in the pattern- and the metacontrast masking conditions for those trials in which T1 was reported correctly is shown in Fig. 3. The results were analyzed in a 2 (type of masking: pattern and metacontrast) × 3 (lag: 100, 300, and 700 ms) ANOVA. The analysis revealed significant effects of type of masking, $F(1,14) = 8.07$, $p = .013$, $MS_e = .004$, lag, $F(2,28) = 34.97$, $p < .001$, $MS_e = .005$, and interaction, $F(2,28) = 4.2$, $p < .05$, $MS_e = .004$.

Figure 3. **Mean percentages of T2|T1 correct responses as a function of Lag and type of mask in Experiment 1.**



These results show that both pattern and metacontrast masking of T2 can mediate the AB deficit. Thus, it can be inferred that both forms of masking can interfere with the contents of the PCB. It is notable that in both cases, there was virtually no masking at Lags 1 and 7. This indicated that masking, whether by pattern or metacontrast, was enabled only during the period of the AB.

As suggested by the significant interaction effect, pattern masking produced a stronger AB than metacontrast masking. This was evidenced by the finding that performance at Lag 3 was significantly less accurate with the pattern mask, while performance at Lag 7 was comparable for the two masks. From this, we can infer that pattern masking seems to be more efficient in interfering with the information stored in the PCB.

This conclusion, however, is questioned by the evidence in Figure 3 that performance at Lags 1 and 7 was obviously constrained by a ceiling imposed by the 100% response scale. It is possible that, were it not for the ceiling constraints, the two functions in Figure 3 might have differed from one another but might have remained parallel throughout the lag domain. It goes without saying that such a finding would lead to the fundamentally different conclusion that the two forms of masking, while differing in overall level, yield comparable AB deficits.

Experiment 2 was designed to avoid the ceiling constraint by increasing the difficulty of the T2 task. This was done by replacing the digit distractors with pseudoletters that are more confusable with letters than are digits. It is known that increasing the similarity between targets and distractors leads to a corresponding increment in the difficulty of identifying T2 (Visser, Bischof, & Di Lollo, 2004). On this reasoning, we expected T2 performance to be brought below ceiling.

3: EXPERIMENT 2

3.1 Method

3.1.1 Participants

Twenty-seven undergraduate students participated in this experiment. They were drawn from the same population as in Experiment 1.

3.1.2 Apparatus and stimuli

The target letters were the same as in Experiment 1 but the distractors were black pseudoletters of similar size (maximum 1º × 1º) and line thickness as the target letters. The pseudoletters are illustrated in Fig. 4. The number of distractors preceding T1 was determined in the same way as previous experiments. On any given trial, the distractors were selected randomly, with replacement, from a set of twenty-two pseudoletters, with the constraint that the selected distractor was not one of the two preceding items. The other parameters of the RSVP stream were the same as in Experiment 1.

Two types of masking were used: pattern and metacontrast masking. The pattern mask was a pseudoletter selected randomly from the set of pseudoletters with the constraint that the selected distractor was not the same as the preceding distractor. The metacontrast mask was the same as in Experiment 1.

Figure 4. **Pseudoletters used as distractors in Experiment 2.**

3.1.3 Design and procedure

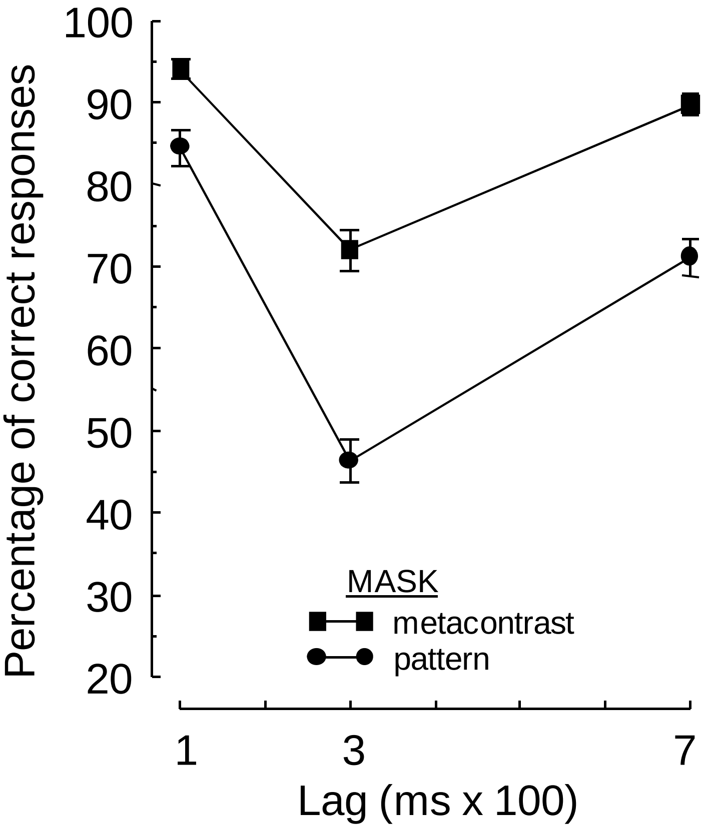
The experiment comprised two blocks: pattern and metacontrast masking. Except for the pseudoletter distractors, the design and procedure were the same as in Experiment 1.

3.2 Results and discussion

The mean T2 accuracy in the pattern and the metacontrast-masking conditions for those trials in which T1 was reported correctly is shown in Fig. 5. The results were analyzed in a 2 (type of masking: pattern masking and metacontrast masking) × 3 (lag: 100, 300, and 700 ms) ANOVA. The analysis revealed significant effects of type of masking, $F(1,26) = 162.9$, $p < .001$, $MS_e =$

.008, lag, $F(2,52) = 133.88$, $p < .001$, $MS_e = .010$, and interaction, $F(2,52) = 12.74$, $p < .001$, $MS_e = .007$.

Figure 5. **Mean percentages of T2|T1 correct responses as a function of Lag and type of mask in Experiment 2.**



The results replicated the findings in Experiment 1 that both pattern and metacontrast masking interfered with the contents of the PCB. This demonstrated that masking, whether by pattern or metacontrast, was enabled only during the period of the AB.

In this experiment, the observers' performance at Lags 1 and 7, although slightly lower than in Experiment 1, were still quite high and close to 100%, at least with metacontrast masking. In other words, pseudoletters were not successful in lowering T2 performance from the high levels observed in Experiment 1. Therefore, it is likely that T2 performance at these lags was still constrained by the ceiling imposed by the upper limit of the response scale. If T2 accuracy were not so limited, we might have found parallel functions for the two types of mask across all three lags. Thus, the significant interaction between lag and type of mask cannot be necessarily attributed to a difference in the magnitude of AB deficit produced by pattern and metacontrast masks. Consequently, it cannot be inferred that these two forms of masks differ significantly in the degree of their interference with the information held in the PCB.

In order to avoid this ceiling constraint, in the next experiment we set out to use an alternative dependent measure that is not constrained by ceiling effect.

4: EXPERIMENT 3

Parameter Estimation by Sequential Testing (PEST) is an adaptive method to estimate the level of an independent variable, L_t , e.g. inter-stimulus interval (ISI) between target and mask, that results in a pre-specified target probability, P_t, that a related event will occur on a single discrete trial, e.g. correct identification of the target (Taylor & Creelman, 1967). Generally, in most of the adaptive estimation methods, an arbitrary initial level of L_t is chosen to be tested in a sequence of trials that result in one value of L_t. After some finite number of trials, a new testing level is chosen that depends on the results of testing at the initial level. During the testing session, trials are performed at each of a series of testing levels where the history of performance determines the subsequent new level. When the specific criteria of the method indicate that the sequence is finished, a value of L_t is calculated (Taylor & Creelman, 1967).

PEST uses a sequential likelihood-ratio test, called the *Wald test* (Wald, 1947), to determine whether the current testing level results in an event probability greater or less than P_t. The Wald test is a maximally efficient test that uses as few trials as possible to produce a decision of any given power (Taylor & Creelman, 1967). With each new testing level, the method keeps a running count of the number of correct responses, N_c, and the total number of trials. After each response, the Wald test defines a permissible range for N_c. If N_c falls within that range, another trial is run at the same testing level, and if it reaches or passes the upper limit of that range, the Wald test decides that the current level is too high. Similarly, if N_c is on or below the lower limit, the Wald test determines the current level to be too low. When such decision is made by the Wald test, a step is made in the appropriate direction, e.g. if the current level is taken to be too high, it will be decreased by a certain step, and testing re-starts at the new testing level. While the size of the first step can be arbitrary, the step sizes after the first are determined by the history of the run (Taylor & Creelman, 1967). The following rules have been shown to be most efficient in implementing PEST:

1) Upon each reversal of step direction, the step size is halved;

2) If a second step is justified in a given direction, it will have the same size as the first;

3) The fourth and subsequent steps in a given direction are double their preceding steps;

4) Regarding the third step in a given direction, if the step preceding the most recent reversal resulted from a doubling, then the third step is the same as the second, while if the step preceding the most recent reversal was not the result of doubling, then the third step will be double the second;

5) When the step size reaches a predetermined minimum level, PEST stops. The minimum step size determines the precision of the final estimate of L_t (Taylor & Creelman, 1967).

We attempted to use the PEST algorithm and parameters suggested by Taylor and Creelman (1967) to compare estimates of the ISI between T2 and the pattern or metacontrast mask in an AB paradigm required to yield a T2 accuracy of 80% (P_t = .80), the critical ISI ($\mathrm{ISI_c}$). Pilot studies using the same timing parameters as in Experiments 1 and 2 showed that PEST could be used with pattern masking but not with metacontrast masking because with metacontrast masks T2 performance never fell below 80%. Therefore, following the practice of Nieuwenstein, Potter, and Theeuwes (2009), we reduced the duration of T2 to a single frame (17 ms) and increased the duration of the mask to 300 ms. This allowed T2 accuracy to fall below 80% at each lag, at least occasionally and, therefore, to provide the possibility of converging on the $\mathrm{ISI_c}$.

4.1 Method

4.1.1 Participants

Twenty-four undergraduate students participated in this experiment. They were drawn from the same population as in previous experiments. Participants were randomly assigned to one of the two groups, each with 12 participants, performing a PEST procedure at each lag with either pattern or metacontrast masking of T2.

4.1.2 Apparatus and stimuli

The displays and RSVP streams were the same as in Experiment 2 except for the following: T2 and the mask were presented for 17 and 300 ms, respectively. The ISI between T2 and the mask was varied by PEST. In each group, three concurrent and randomly interleaved PEST sequences were run to estimate the $\mathrm{ISI_c}$ required to yield a T2 accuracy of 80% at each of the three lags.

The ISI_c at each lag was calculated as the average of the ISI in twelve trials after the third reversal.

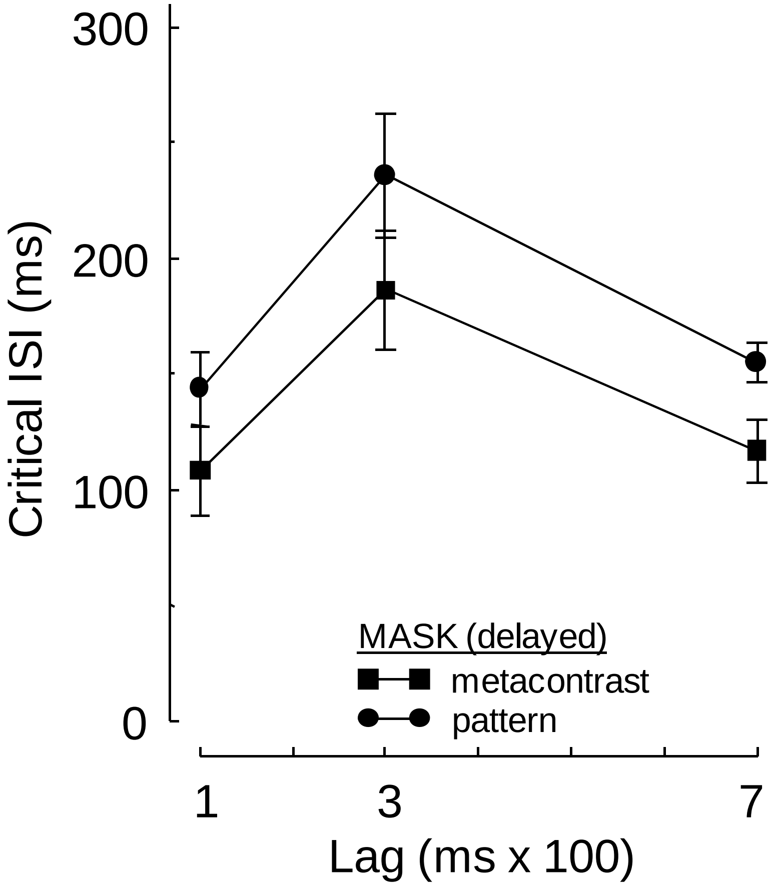
4.1.3 Design and procedure

Each participant completed one PEST run with either pattern or metacontrast mask after T2. There were 10 practice trials at the beginning of each session. These were followed by a maximum total of 300 PEST trials, 100 for each lag. If PEST had not terminated within 300 trials, the session was ended. PEST would continue on Lags 1, 3 and 7 until the ISI_c was calculated for all three lags.

4.2 Results and discussion

The ISI_c in the pattern and the metacontrast-masking groups are shown in Fig. 6. The results were analyzed in a 2 (type of masking: pattern and metacontrast masking) × 3 (lag: 100, 300, and 700 ms) ANOVA with type of masking as a between-subjects and lag as a within-subjects factor. The analysis revealed significant effects of type of masking, $F(1,28) = 5.98$, $p = .02$, $MS_e = 9832.75$, and lag, $F(2,56) = 29.80$, $p < .001$, $MS_e = 2849.76$, but not a significant interaction, $F < 1$.

Figure 6. **Mean ISI$_c$ as a function of Lag and type of mask in Experiment 3.**



The results showed that in both groups, the ISI$_c$ at Lag 3 was significantly longer than at Lags 1 and 7. Namely, in both groups, the interval between the target and the mask at Lag 3 needed to be longer than at Lags 1 and 7 to result in a comparable T2 accuracy. Therefore, it can be inferred that the processing of T2 and the buffering of its information in the PCB took longer at Lag 3 than at Lags 1 and 7 with both forms of masking. This confirmed the findings in Experiments 1 and 2 demonstrating the ability of pattern and metacontrast masking to interfere with the T2 representation held in the PCB during the period of the AB.

Although the overall ISI_c was lower with metacontrast than with pattern masking, the ISI_c functions in the two groups were parallel throughout the domain. Conventionally, AB magnitude has been defined as the difference between the lowest T2 performance and performance outside the period of the AB (in the present context, Lag 3 and Lag 7, respectively). Thus, the lack of interaction between lag and type of masking indicates that pattern and metacontrast masking produced AB deficits of comparable magnitude. Therefore, it can be concluded that the amount of delay in T2 processing at Lag 3 caused by the mask compared to Lag 7 did not significantly differ between the two forms of masking. Consequently, it can be inferred that pattern and metacontrast masking interfered with the contents of the PCB to a similar extent.

5: EXPERIMENT 4

The first three experiments examined the ability of delayed forms of pattern and metacontrast masks to produce an AB deficit. One important characteristic of the masking paradigm in those experiments was the delay inserted between T2 and the mask (i.e., a 50-ms blank interval). That delay ensured that the onset transients produced by the mask were temporally separated from those triggered by T2 (Phillips & Singer, 1974a). As mentioned before, such unique transient activity in response to the onset of the mask have been suggested to produce masking by inhibiting the sustained activity triggered by the target (e.g., Breitmeyer & Ganz, 1976).

In order to investigate the necessity of mask-induced onset transients to interfere with the T2 representation in the PCB, we used a third form of masking, namely COM. A critical difference between COM and the two previous masking paradigms is the simultaneous presentation of target and mask in the former. In a COM paradigm, onset transients are generated by the combined target-mask configuration, but not by target or mask alone. In other words, there is no transient activity uniquely triggered by the mask onset to inhibit the ongoing target-related activity. Thus, if COM is shown to produce an AB deficit, it can be concluded that mask-induced onset transients are not necessary to interfere with the T2 representation in the PCB. Furthermore, it can be inferred that OSM by itself can interrupt the preconscious processing of T2. Such finding would provide evidence for interfering with the PCB at high levels of visual processing.

Experiment 4 was designed to examine the effects of common-onset and delayed metacontrast masking on T2 performance in an AB paradigm. In order to compare the results with those obtained with delayed pattern and metacontrast masking (Experiment 2, Fig. 5), similar RSVP parameters were used as those in Experiment 2.

5.1 Method

5.1.1 Participants

Participants were recruited in the same way as in previous experiments. Eighteen participants were assigned to the Delayed-mask group, and fourteen to the Common-onset-mask group.

5.1.2 Apparatus and stimuli

The RSVP stream was the same as in Experiment 2 except for the type of masking. In the Delayed-mask group, the type of masking was similar to that in the metacontrast masking condition in Experiment 2. In the Common-onset-mask group, the mask was presented simultaneously with T2 and remained on the screen for 300ms while T2 disappeared 50ms after its onset.

5.1.3 Design and procedure

Each participant completed one block with either delayed or common-onset metacontrast mask. There were 10 practice trials at the beginning of each session. These were followed by a total of 120 trials, 40 for each of the three lags.

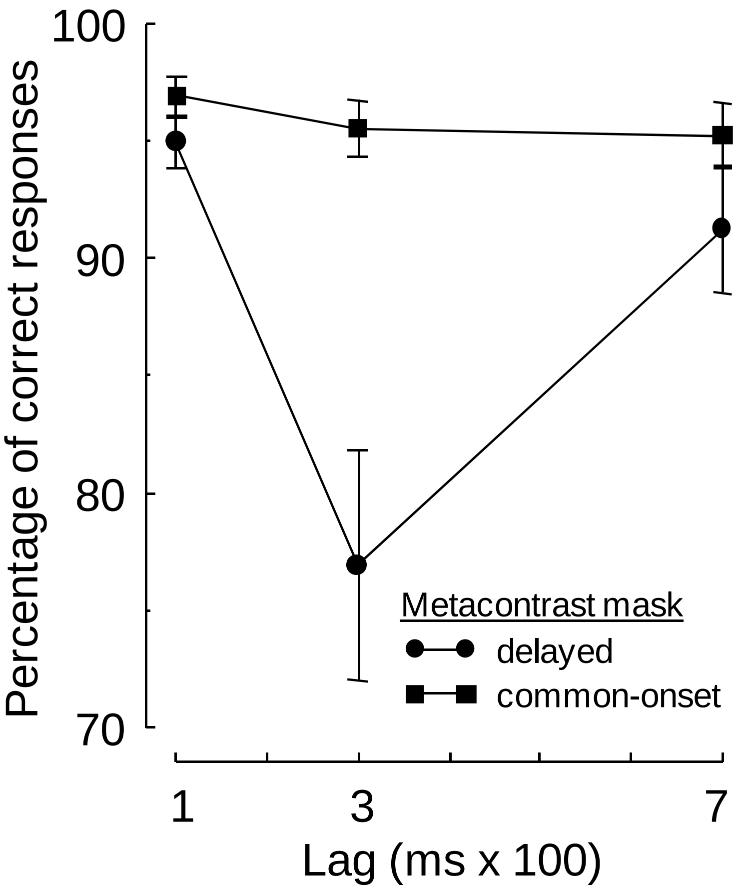
5.2 Results and discussion

The mean T2 accuracy for those trials in which T1 was reported correctly is shown in Fig. 7. The results were analyzed in a 2 (type of masking: delayed metacontrast and common-onset metacontrast masking) × 3 (lag: 100, 300, and 700 ms) ANOVA with type of masking as a between-subjects and lag as a within-subjects factor. The analysis revealed significant effects of type of masking, $F(1,30) = 14.34$, $p =.001$, $MS_e =.01$, lag, $F(2,60) = 14.07$, $p < .001$, $MS_e = .01$, and interaction, $F(2,60) = 11.87$, $p < .001$, $MS_e =.07$.

Besides replicating the findings of Experiment 2 with delayed metacontrast masking, the results show a largely reduced AB deficit with common-onset masking compared with delayed masking. These findings are consistent with the hypothesis that the unique onset transient produced by the mask is necessary to interfere with the information held in the PCB in order to produce an AB deficit.

However, these results also show that, as with delayed metacontrast mask in Experiment 2, using pseudoletters as distractors instead of digits in a COM paradigm did not succeed in bringing T2 performance below ceiling. Thus, the significant reduction in the magnitude of AB deficit in common-onset masking can be due to T2 performance at Lags 1 and 7 being constrained by a ceiling effect. Therefore, one could argue that were it not for the ceiling constraints, the common-onset mask might have produced an AB deficit of a magnitude comparable to that produced by the delayed mask. We address this issue in the next experiment.

Figure 7. **Mean percentages of T2|T1 correct responses as a function of Lag and type of mask in Experiment 4.**



6: EXPERIMENT 5

In Experiment 5, we used PEST to avoid ceiling effects in examining the ability of common-onset metacontrast masking to produce an AB deficit, in comparison with delayed metacontrast masking.

6.1 Method

6.1.1 Participants

Fifteen undergraduate students participated in this experiment. They were drawn from the same population as in previous experiments.

6.1.2 Apparatus and stimuli

The RSVP stream was the same as in Experiment 3 except for the form of masking: Here, the masks were presented simultaneously with T2 and remained on the screen for a varying duration governed by PEST, while T2 disappeared 17 ms after its onset.

The PEST procedure was the same as in Experiment 3 except that PEST varied the duration of the mask to yield a T2 accuracy of 80%. Such critical mask duration was measured in a way similar to the measurement of ISI_c in Experiment 3.

6.1.3 Design and procedure

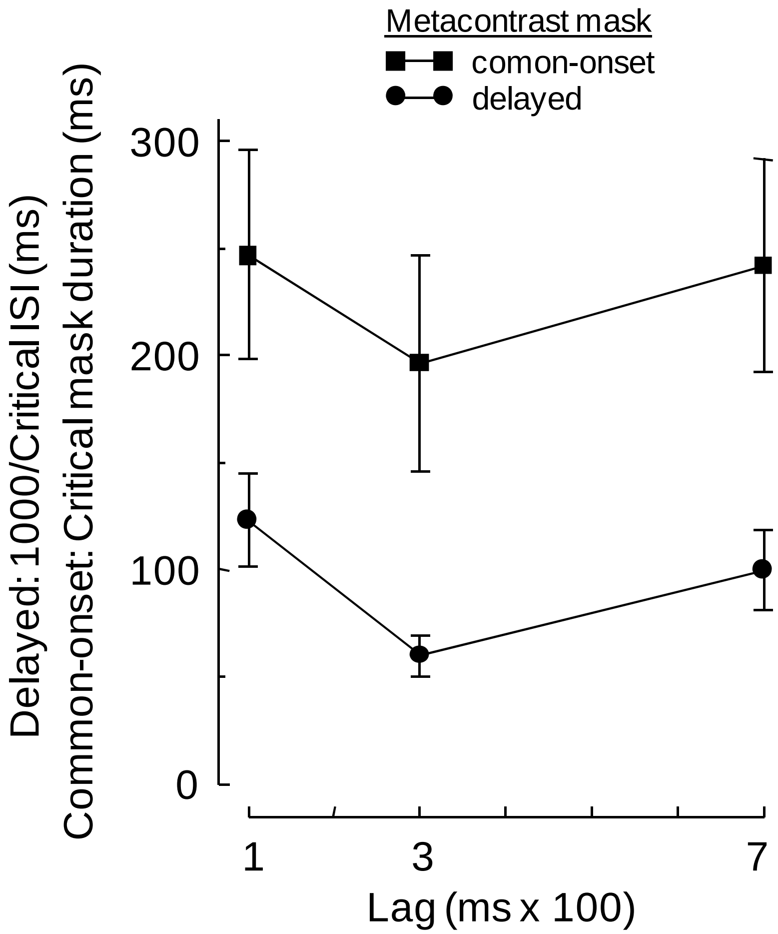
With the changes noted above, the design and procedure was the same as in Experiment 3.

6.2 Results and discussion

The critical mask durations estimated by PEST at Lags 1, 3, and 7 are illustrated in the upper section of Fig. 8. The results were analyzed in a repeated-measures ANOVA with lag as a within-subjects factor. The analysis revealed a significant effect of lag, $F(2,28) = 3.46$, $p < .05$, $MS_e = 3353.08$. Furthermore, testing the within-subjects contrast revealed a significant quadratic component of lag, $F(1,14) = 5.15$, $p = .04$, $MS_e = 2238.71$. These results demonstrate that common-onset metacontrast masking can produce an AB deficit.

However, the critical mask durations measured in this experiment cannot be directly compared to the ISI_c measured in Experiment 3. This is because the strength of COM increases with the duration of the common-onset mask. In contrast, in the delayed-masking paradigm, the strength of masking decreases as the ISI between target and mask is decreased. In other words, the probability of correct T2 identification is inversely related to the duration of a common-onset mask, but is directly related to the duration of ISI in a delayed masking paradigm.

Figure 8. **1000/Critical ISI (delayed metacontrast masking) and critical mask duration (common-onset metacontrast masking) as a function of Lag in Experiment 5.**



In order to compare the critical mask durations measured in this experiment with the ISI_c measured in Experiment 3, we calculated the reciprocal of the ISI_c data from Experiment 3, and multiplied them by 1000 to make the two scales comparable. These results from Experiment 3 and the critical mask durations found in Experiment 5 are illustrated in Figure 8 and were compared in a 2 (type of masking: delayed and common-onset masking) × 3 (lag: 100, 300, and 700 ms) ANOVA with type of masking as a between-subjects and lag as a within-subjects factor. The analysis revealed significant effects of type of masking, *F*(1,26) = 6.95, *p* = .01, MS_e = 54247.50, and lag, *F*(2,52) = 8.16, *p* = .001, MS_e = 24550.97, but not a significant interaction, *F*< 1.

The results indicate that common-onset metacontrast masking can produce an AB deficit when not constrained by a response ceiling. Given the data-transformation procedure described above, the significance of the difference in overall level is not meaningful. However, this does not negate the authenticity of the interaction effect. The results show that there was no interaction between lag and mode of masking (delayed or common-onset). This absence of interaction indicates that the magnitude of the AB deficit produced by common-onset masking is comparable to that produced by delayed masking. Therefore, it can be inferred that COM is as effective as delayed metacontrast masking in interfering with the T2 representation held in the PCB. Furthermore, it demonstrates that onset transients uniquely generated by the mask are not necessary for such interference.

At a more general level, the present work provides evidence relevant to the relationship between COM and the distribution of attention. Many studies in the masking literature have shown that a critical requirement for the occurrence of COM is that attention be spatially distributed (Di Lollo et al., 2000; Enns, 2004). The unique contribution of the present work in this respect is the demonstration that COM occurs also when attention is distributed over time, such as during the period of the AB.

7: GENERAL DISCUSSION

7.1 Executive summary

The term *attentional blink* (AB) refers to the phenomenon in which the second of two targets (T2) embedded in a rapidly presented sequence of distractors may be reported incorrectly if presented within about half a second from the first one (T1; e.g., Raymond et al., 1992). The AB literature indicates that there are two critical aspects to this phenomenon: 1) T2 processing is delayed during a brief period following the presentation of T1 (e.g., Ghorashi, Smilek, & Di Lollo, 2007; Jolicœur & Dell'Acqua, 1998; Kawahara, Di Lollo, & Enns, 2001; Vogel, Luck, Shapiro, 1998); 2) T2 representation is vulnerable to masking only during the delay and such masking is necessary to produce an AB deficit (Brehaut, Enns, & Di Lollo, 1999; Giesbrecht & Di Lollo, 1998). These findings support the hypothesis that the underlying cause of the AB is backward masking of T2 during the delay following T1 presentation. On this view, the AB should not be considered as a unitary phenomenon, but one that arises from two independent factors, namely, Psychological Refractory Period (PRP; e.g., Telford, 1931) and backward masking (e.g., Breitmeyer, 1984).

Most current theories of the AB, while attempting to account for the delay in T2 processing, have not integrated the masking of T2 into the core of their conceptual framework (e.g., Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; Di Lollo, Kawahara, Ghorashi, & Enns, 2005). Therefore, these models do not explain why the AB depends critically on masking of T2 during the delay, and, consequently, they cannot be considered as complete models of the AB.

Several studies have demonstrated that missed T2's during the AB are still registered in the brain (e.g, Luck et al., 1996; Marois et al., 2004; Shapiro et al., 1997). Therefore, during the period of delay in T2 processing, the representation of T2 must be stored in a temporary buffer until it receives attention and T2 processing can be completed. This stage of processing corresponds to a '*preconscious'* stage described recently by Dehaene et al. (2006), during which the representation of a stimulus is maintained temporarily-active for a few hundred milliseconds in a buffer, i.e. preconscious buffer (PCB) as we call it. The information held in the PCB cannot be accessed consciously at the moment, but can become consciously available if it receives top-down attentional amplification.

Considering the critical role of backward-masking in the AB, and the importance of studying the characteristics of the PCB in understanding the underlying mechanisms of the AB, we investigated how the main types of backward masking could interfere with the T2 representation stored in the PCB during the period of the AB. Specifically, in five experiments, we studied the effects of masking of T2 by pattern, metacontrast and common-onset metacontrast in an AB paradigm.

Almost all AB studies in the literature have used pattern masking after T2. Experiment 1 provided the first demonstration that an AB deficit can be produced by metacontrast masking of T2. Because of a significant interaction between lag and type of mask, the magnitude of that deficit seemed to be smaller than the one produced by pattern masking. However, due to a ceiling effect on T2 performance at Lags 1 and 7, the difference in the magnitude of the AB deficit caused by pattern and metacontrast masks was not reliable.

Experiment 2 was designed to avoid such ceiling constraints by making the identification of the target letters more difficult. This was done by using pseudoletter distractors instead of digits, thereby increasing the target-distractor similarity. As in Experiment 1, both pattern and metacontrast masks produced an AB deficit with a significant interaction effect. Although T2 performance at Lag 3 was lower than in Experiment 1, it remained close to ceiling at Lags 1 and 7. Therefore, the apparent difference in AB magnitude between the two types of masking could still be attributed to ceiling constraints.

Experiment 3 resolved the issue of performance at ceiling by using PEST, which, by definition, is not constrained by ceiling considerations. PEST calculated the critical ISI (ISI_c) at each lag required to yield a T2 performance of 80%. The results confirmed that an AB deficit could be brought about by either type of mask. Critically, however, no interaction was found between lag and type of mask. In other words, the magnitude of the AB deficit produced by the metacontrast mask was as large as that produced by the pattern mask. This can be taken to mean that the duration of the delay in T2 processing at Lag 3 caused by the mask was similar with pattern and metacontrast masks. Consequently, metacontrast masking was shown to interfere with the representation held in the PCB to a degree similar to pattern masking.

In both pattern and metacontrast masking, the onset of the mask generated transient activity that might have inhibited the ongoing sustained activity related to target processing. Experiment 4 investigated the necessity of such mask-induced onset transient in producing an AB deficit. This was achieved by including COM in which there was no onset transient generated separately by the mask. On the face of it, the results showed a lack of an AB deficit with common-onset masks. However, since T2 performance at all three lags was close to ceiling, it could be argued that absence of an AB deficit could have reflected a ceiling effect. Namely, but for ceiling constraints, an AB deficit might have been in evidence with common-onset masking.

Ceiling effects were avoided in Experiment 5 by using PEST to examine the possibility of an AB deficit with common-onset masking of T2. The results revealed an AB deficit caused by common-onset masking. This was the first demonstration of an AB deficit obtained with common-onset metacontrast masking. The magnitude of the AB deficit was not different from the magnitude of the AB produced by delayed metacontrast masking. These findings disconfirmed the necessity of onset transients produced uniquely by the mask to interfere with the contents of the PCB. Furthermore, they indicated that the PCB can be interfered with at high levels of visual processing, such as iterative reentrant activity involved in object-substitution masking.

7.2 The locus of the PCB

According to iterative reentrant accounts, the initial low-level activity caused by the onset of a display generates a feed-forward sweep that activates tentative high-level representations, i.e., *perceptual hypothese*s. Because of their multiplicity and ambiguity, these hypotheses need to be confirmed through iterative comparisons between the ongoing activity at early sensory levels and the reentrant signals from higher levels of the visual system (e.g., Di Lollo et al., 2000; Fahrenfort, Scholte, & Lamme, 2007; Lamme & Roelfsema, 2000).

As described above, in the context of COM in the AB paradigm, the continued presence of the mask after the disappearance of T2 creates a mismatch with the reentrant signals that leads to object-substitution masking (Di Lollo et al., 2000). It has been shown that COM is largely insensitive to low-level factors such as contour proximity and stimulus luminance, whereas it is affected by high-level factors such as spatial distribution of visual attention (Enns, & Di Lollo, 1997). Such findings indicate that COM operates at higher levels of visual information processing. Therefore, since we demonstrated in Experiment 5 that COM can interfere with the representation of T2 held in the PCB, our results strongly suggest a high-level locus for the PCB within the visual system.

In Experiments 1, 2, and 3, we found that delayed pattern and metacontrast masking can also interfere with the PCB. In considering the significance of these outcomes for determining the locus of the PCB, it is well to be reminded that both metacontrast and pattern masking can be mediated, at least in part, by low-level processes. We have seen that metacontrast masking is based largely on low-level processes such as lateral inhibition between neurons representing the contours of target and mask (Breitmeyer, 1984; Weisstein, Ozog, & Szoc, 1975) and the inhibitory effect of the mask-triggered onset transients on the target-related sustained activity (Enns & Di Lollo, 2000). Similarly, pattern masking can also be mediated, at least in part, by low-level processes such as temporal integration of target and masking contours (Spencer & Shuntich, 1970), as well as by incidental spatiotemporal relationships between the contours of the target and those of the mask that may yield metacontrast-like effects.

However, in light of the results of Experiment 5, the interference with the PCB by pattern and metacontrast masking observed in the first three experiments cannot be taken as unambiguous evidence for a low-level locus of the PCB. This is because it is plausible that in order to buffer the representation of T2 during the period of the AB, the PCB has to receive input signals from lower levels. Those signals might carry information that are involved in *object formation* (e.g. Enns, 2004). When such input from early visual areas are impaired by low-level masking, the PCB cannot receive the information it needs to buffer the representation of T2 during the AB.

In summary, the evidence from COM strongly suggests a high-level locus for the PCB. The finding that low-level masking by pattern and metacontrast masks impairs accuracy of T2 identification must then be ascribed not to interference with the contents of the PCB but with the availability of low-level information required by the PCB in order to buffer T2 representation.

7.3 Implications for current theories of the AB

7.3.1 Bottleneck theories

According to bottleneck theories of the AB, in order for T1 to be available for conscious report it needs to be consolidated in the visual short-term memory (VSTM; Chun & Potter, 1995; Jolicoeur & Dell'Acqua, 1998). The process of consolidation requires limited-capacity resources that are not sufficiently available for T2 while the high-level processing stage is busy with the first target. While so delayed, the representation of T2 remains vulnerable to being overwritten by the subsequent item in the RSVP stream (that has been shown to act like a mask, Brehaut, Enns, & Di Lollo,1999; Dell'Acqua, Pascali, Jolicœur, & Sessa, 2003; Giesbrecht & Di Lollo, 1998; Grandison, Ghirardelli, & Egeth, 1997; Seiffert & Di Lollo, 1997). Specifically, according to two-stage models of the AB, the items in an RSVP stream are processed in parallel in Stage 1 (e.g. Chun & Potter, 1995). Stage 2, however, is a limited-capacity serial stage that begins only when Stage 1 indicates the probable presence of a target, e.g. T1. While processing T1, Stage 2 is not accessible to any items currently in Stage 1, i.e., T2. An exception to this rule is the item that comes directly after T1 in the RSVP stream, which, in the case of T2, gives rise to Lag-1 sparing. The essential point here is that while delayed in Stage 1, the T2 representation is impaired through overwriting or decay.

These models can explain the results of Experiment 3 with pattern masking, i.e., at Lag 3 the onset of the mask must be delayed because Stage 2 is still unavailable for T2 and, therefore, T2 cannot leave Stage 1 and remains vulnerable to masking until it can gain access to Stage 2.

As it stands, however, these accounts cannot explain the effect of metacontrast masking for the simple reason that T2 cannot be overwritten by a mask that does not overlap with it. At the very least, two-stage models need to be revised with regard to the type of masking that can take place in Stage 1. What needs to be stated explicitly is that contour formation takes place in Stage 1 and because metacontrast masks interfere with the process of contour formation, metacontrast masking occurs in Stage 1. The longer ISI_c at Lag 3 in metacontrast masking can then be explained in the same manner as for pattern masking.

Two-stage models cannot account for common-onset metacontrast masking because they provide no mechanism that can mediate this type of masking in Stage 1. Namely, what is processed in Stage 1 is both the target and the metacontrast mask, and the combined image would then gain access to Stage 2 with consequent absence of masking. This prediction is inconsistent with the results of Experiment 5 where common-onset metacontrast masking interfered with T2 processing as efficiently as delayed metacontrast masking. Since there was no overlap between the contours of target and mask, the representation of T2 could not be overwritten by the mask. In addition, since there was no onset transient uniquely produced by the mask, the ongoing sustained activity related to target processing could not be inhibited by such onset transients.

To explain these results, we have argued for an object-substitution account based on the mismatch between reentrant signals from higher levels and the low-level activity generated by the mask alone. However, in two-stage models, there is no explanation for interference with T2 processing caused by high-level reentrant signals in the absence of overwriting of the target and mask-induced onset transients. Therefore, two-stage accounts need to be revised to account for the role of such signals from higher levels in interfering with the processing of a target that has already entered Stage 2.

7.3.2 Resource-depletion theories

According to resource-depletion theories of the AB, the process of consolidation in VSTM can involve multiple items rather than just a single item, including some of the intervening or subsequent distractor items (Raymond, Shapiro, & Arnell, 1995; Shapiro & Raymond, 1994; Shapiro, Raymond, & Arnell, 1994). The items that enter VSTM compete for attentional resources that make them available for conscious access and report. One of the factors that influence the outcome of this competition is the order of presentation, i.e., earlier items receive more resources. Since the total resources available within VSTM is limited, when most of them are allocated to earlier items such as T1 there may not be sufficient resources for subsequent targets such as T2. The failure of a target to enter VSTM results in impaired target identification.

These theories account for the effect of pattern mask such as a digit or pseudoletter entering VSTM after T2. Supposedly, when T2 is followed, in rapid succession, by such an item, the amount of processing resources required to process T2 increases. Therefore, there will be a lower probability that T2 receives adequate resources when presented at Lag 3, and will not be reported correctly more often. At longer lags, the items are said to be flushed from VSTM thus making resources available for subsequent targets (e.g., T2 at Lag 7). Resource-depletion theories may be made to account for the AB obtained when T2 is followed by a metacontrast mask, by hypothesizing that since the stage of object formation for T2 is impaired, T2 processing needs more processing resources to be completed. This leads to a deficit in T2 identification at Lag 3, when T1 and its following item(s) have already been assigned most VSTM resources.

However, resource-depletion theories do not explicitly explain how the competition for attentional resources occurs when T2 is presented simultaneously with a metacontrast mask. Such theories do not address the role of reentrant signals from higher levels in influencing the allocation of resources available within VSTM. It is possible that in order for an item in VSTM to receive adequate resources, there must be a continued match for a certain period of time between the ongoing low-level activity caused by the current items and the iterative recurrent signals from higher levels. This confirmation might be necessary for the transfer of information from VSTM to working memory where the information is available for conscious access and report.

7.3.3 Input control theories

Recently, several studies have revealed that accounts based on T1-induced resource deficiency cannot be considered as a sufficient or even necessary explanation of the AB. For example, Di Lollo et al. (2005) used an RSVP stream of distractors in which three items were embedded. In one condition, a distractor was inserted between two targets (i.e. T1 D T2). As previously observed in typical AB paradigms, T2 performance was significantly lower relative to T1. When, in another condition, the items were three consecutive targets (i.e. T1 T2 T3) T3 performance was not significantly different from that for T1. In other words, although T3 was in exactly the same temporal position relative to T1 as was T2 in the previous condition, there was no AB. However, if a T1-induced resource deficiency was responsible for the AB deficit, a similar decrease in T3 performance should have been observed, especially considering the additional resources required to process T2.

Di Lollo et al. (2005) argued that there was no insufficiency of resources to process several consecutive (at least more than two) targets in an RSVP stream. Instead, they suggested a temporary loss of control (TLC) account in which the AB occurs when the endogenous attentional control settings are disrupted by the intervening distractors. According to this account, in order to filter the information in the RSVP sequence, the participants set up an input filter that accepts items in the target category and rejects items in the distractor category. Critically, a certain amount of executive control is required to maintain such an attentional set. When a target is presented in the RSVP stream for the first time, these executive control signals are required for processing that target. As long as the following items are all targets, without any intervening distractor, the same executive functions can be used for target processing. However, when the first post-T1 distractor is presented, it exogenously disrupts the input filter because the system has to be reconfigured from an acceptance-mode to a rejection-mode. This disruption affects the processing of subsequent targets, hence the lower T2 performance at short lags, e.g. Lag 3. When sufficient time is available for reconfiguration, the attentional control is recovered and the input filter is reinstated, hence the high T2 performance at long lags such as Lag 7. Therefore, according to the TLC account, the AB is not caused by the limited attentional resources required for processing individual targets. It is caused, instead, by a limitation of the executive control functions that can only handle one aspect of the task (target identification, input control) at any given moment (Di Lollo et al., 2005; Kawahara, Enns, & Di Lollo, 2006).

Similarly, Olivers, van der Stigchel, & Hulleman (2007) suggested that observers in an AB paradigm set up an attentional set for targets and against distractors. Such an attentional set can be viewed as a template or input filter, based on which, target properties are enhanced and distractor properties are rejected. The observed behavioural results in the RSVP task depend critically on the criteria used by the attentional set. If they are set too strongly for the target category, then the distractors resembeling a target can spuriously trigger the higher levels of target processing (Visser, Bischof, & Di Lollo, 2004). On the other hand, if such criteria are set too strongly against selecting distractors, some targets may not get selected if they do not carry sufficient evidence for belonging to the target category.

Importantly, Olivers et al. (2007) assumed that selection of a target item by the input filter results in the loosening of the control over the input filter. They argued that such loosening, or opening of the *attentional gate*, is not because of a loss of control, but because the incoming perceptual evidence indicates the presence of relevant information in the RSVP stream. Similarly, they assumed that when the input filter incidentally selects a distractor, the input control is automatically, but temporarily, tightened, i.e. the attentional gate closes. Therefore, Olivers et al. (2007) explained the AB as follows: when the first target in the RSVP stream, i.e. T1, is presented and selected by the input filter, the control over the input filter is loosened. This allows the item immediately following T1 to enter. If the following item that enters the system is also a target, its processing can proceed easily. However, if that item is a distractor, the erroneous selection results in overly correcting the input filter criteria and temporarily closing the attentional gate. Such a closure impairs the selection of the subsequent targets, hence the AB. The degree of such opening and closure of the attentional gate is contingent upon the criteria used by the attentional set. Although the principal idea in this account is similar to the TLC account, the difference is that Olivers et al. (2007) suggest that the first post-T1 distractor results in an overzealous application of the attentional set, i.e. a temporary tightening of the control over the input filter rather than to a loss of control.

These theories do not address the effect of different forms of masking of post-T1 target items, particularly delayed and common-onset metacontrast masking, on the dynamic and automatic changing of the input filter in the RSVP paradigm. Specifically, it is not clear how re-setting the input filter too strongly for target properties after presenting T2 can lead to the entrance of a delayed metacontrast mask that shares no contours with T2. The significantly different properties of such mask means that it should be unambgiuously distinguished from the targets. In other words, since such a mask does not resemble a target, it cannot supriously induce higher levels of processing typically reserved for targets. If anything, the metacontrast should be rejected more easily than digit or pseudoletter distractors in the RSVP stream. Also, it cannot be argued that the metacontrast mask takes advantage of the re-loosened control over the input filter induced by T2, thereby low-level masking T2 and impairing its processing. This is because no T2 masking by metacontrast occurs outside the period of the AB, i.e. at long lags such as Lag 7.

The effect of common-onset masking of T2 has not been addressed by input-control theories either. Since in COM, the metacontrast mask is presented at the same time as T2, it enters while the input filter is loosely set for selecting targets, and, therefore, it cannot affect the degree of opening or closure of the attentional gate. It is possible that the functioning of such a gate is not as automatic and exogenously-controlled as current input filter theories suggest. Plausibly, the reentrant signals from higher levels affect the degree of applying control over the input filter, and perhaps the criteria used by the attentional set themselves. At short lags, if T2 and a metacontrast mask are presented together, the attentional set needs to be rapidly reconfigured from rejecting distractors to accepting T2 as a target. It is possible that for a certain period of time, this reconfiguration needs to be supported by matching reentrant signals from higher levels of visual processing or the central executive itself. When T2 disappears, the continued presence of the mask alone might give rise to reentrant signals that no longer match the current attentional set, thereby disrupting the process of reconfiguration required for processing T2.

7.4 Some additional considerations

In Experiments 1 and 2, pattern masking seemed to be stronger than metacontrast masking in the overall performance at Lag 3. It could be argued, however, that this difference may not represent the true difference between the two forms of masking because the ISI employed in the experiment may not have been optimal for metacontrast or, for that matter, for pattern masking. Although valid, this concern cannot apply to Experiment 3 because the PEST technique automatically seeks the optimal ISI.

In a related point, the ISI_c for metacontrast masking in Experiment 3 ranged between ~ 100 ms and 175 ms that corresponds to an SOA range between ~ 115 and 190 ms. This range of SOAs is beyond the conventional range for metacontrast masking, which typically has an upper limit of about 100 ms (Breitmeyer, 1984). It should be noted, however, that leading streams of distractors had never been used in earlier studies of metacontrast masking. From this perspective, the relatively long ISI_cs obtained in the present work can plausibly be ascribed to an additional delay in the processing of T2 due to the switch from rejecting the distractors before T2 to processing T2 itself (Kawahara et al., 2006).

7.5 Concluding remarks

Throughout the present work, we have argued that the root cause of the AB is masking of T2 when it is presented shortly after T1. Extant theories have acknowledged the necessity of masking, but have not incorporated it within their conceptual frameworks. Consequently, there has been a dearth of research into the role of masking – and of different forms of masking – as determinants of the AB. The present work is a first step in this direction. In so doing, we have provided the first demonstration that an AB deficit is obtained with metacontrast masking of T2. In addition, the demonstration that common-onset masking can mediate the AB deficit requires substantial revisions to most current models of the AB. Such revisions, however, are beyond the scope of the present dissertation.

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