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Camp, Sarah-Jayne (2015)
Looking through the crowded mask: investigating the effect of distractor number and position in object substitution masking, PhD, Oxford Brookes University

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Looking through the crowded mask: Investigating the effect of distractor number and position in object substitution masking

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Supervised by Dr Michael Pilling, Dr Luci Wiggs & Dr Sanjay Kumar

This thesis is submitted in partial fulfilment of the requirements of the award of Doctor of Philosophy

November 2015

Acknowledgements

I would firstly like to say that I am unbelievably appreciative of all the participants who took part in my studies that make up this thesis. I must also say how grateful I am to Oxford Brookes University and in particular the studentship funding that they awarded me. I feel honoured to have been given this opportunity.

I have been incredibly fortunate to have been supervised by Dr Michael Pilling, Dr Luci Wiggs and Dr Sanjay Kumar each of whom have been have been an honour to work with and to learn from. I am truly grateful that they have been exceedingly kind, patient and encouraging throughout my PhD. A special mention must also be given to Dr Aspa Paltoglou without whose guidance I could not have succeeded in my EEG analysis.

I would like to say a special thanks to all of my fellow PhD students who have consistently provided support, inspiration and encouragement to me. Thank you in particular to Sarah Mansbridge and Julia Birchenough for helping to break up my day with friendly chatter. Thank you also to Lynsey O'Rourke, Emma Davies and Aspa Paltoglou for the constant supply of tea and encouragement. I would like to say how grateful I am to have such unwaveringly supportive friends and family. Thank you to Charlotte Goodwin for always being there for me, listening and understanding. Thanks to Lauren Bowles, Alex Rein and Michael Ralph for their continued encouragement, constant laughter and wonderfully fun-filled times. Thank you also to my Bismore friends for the constant support and enjoyable times.

I must say a massive thank you to my Mum, Dad, Ian and Enfys without whom I could not have achieved this. I would also like to say how thankful I am to all of the Brooks family for their support. Finally, I must say how truly grateful to and appreciative I am of my partner, Hugo Brooks without whom I could not have completed this thesis. Thank you for your constant faith, support and belief, even when I doubted myself.

Abstract

Object substitution masking (OSM) is a phenomenon wherein a surrounding mask (typically four dots) that onsets with a target but lingers after its offset significantly reduces target perceptibility. OSM was originally postulated to occur only when spatial attention was spread (Di Lollo et al., 2000). Specifically, it was claimed that OSM only occurred when the target was presented in the context of large set-size displays (Di Lollo et al., 2000). However, more recent research has raised questions over the relevance of set size in OSM. Two separate investigations (Argyropoulos et al., 2013; Filmer et al., 2014) found that strong masking by OSM could be produced even with a set size of one. It was argued that the "set size" effects in OSM were actually an artifact of constrained performance. That is, once performance was brought within a measurable range, OSM was reported to be independent of set size. Further research however has suggested that perhaps this rejection of the role of set size in OSM was premature. Pilling (2013) found that increased set size did in fact lead to greater OSM magnitude. Therefore it seems that an explanation of constrained performance cannot fully account for the experimental findings.

This thesis begins by investigating the disparity between these results by further exploring the role of set size in OSM. The first chapter provides an overview of some of the constraints for perceptual awareness by examining experimental phenomena that prevent visual awareness. The experimental phenomena of visual masking and specifically OSM are focused on with particular focus given to the role of attention in OSM. Chapter 2 is the first experimental chapter. This chapter investigates the role of set size in OSM using five experiments. Chapter 3 explores if visual crowding can be used as an alternative explanation for the set size effects in OSM with five experiments. Chapter 4 attempts to investigate the neural underpinnings of OSM, and the interaction between OSM and crowding using an EEG method.

This thesis proposes, based on its findings, that the nominal set size effect in OSM is actually an effect of crowding, a factor which tends to co-vary with set size in most studies. Further experiments in this thesis showed that the interaction between crowding and OSM was one in which OSM affected crowding rather than the converse process. That is, with the use of OSM, the window at which flankers crowd the target becomes extended. These findings show parallels with the previously reported phenomenon of "supercrowding" which has been reported with classical masking. Given this, these results challenge claims regarding the position of OSM and crowding in the object processing hierarchy (e.g. Breitmeyer, 2014). This thesis contributes to the ongoing investigation of OSM, provides implications for its existing theories and for accounts of object processing more generally as well as highlighting future directions for research in this field.

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Glossary of abbreviations

4DM	Four dot mask
AB	Attentional blink
AFC	Alternative forced choice
C	Response bias
CFS	Continuous flash suppression
CMOS	Computational Model of Object Substitution
EEG	Electroencephalography
ERP	Event related potential
ICA	Independent components analysis
ISI	Inter-stimulus interval
IT	Infero-temporal cortex
M cells	Magnocellular cells
N2pc	Negative 200ms posterior-contralateral
OSM	Object substitution masking
OSTM	Object Substitution Theory of Masking
OUT	Object updating theory
P cells	Parvocellular cells
pFA	Proportion of false alarms
pHit	Proportion of hits
PR	Perceptual retouch
SNR	Signal-to-noise ratio
SPCN	Sustained posterior contralateral negativity
SOA	Stimulus onset asynchrony
TMS	Transcranial magnetic stimulation
V1	Primary visual cortex
VAN	Visual awareness negativity
VSTM	Visual short-term memory

Chapter 1| Introduction

This chapter will start by exploring some of the experimental phenomena which constrain the visual system in achieving awareness of what our eyes “see”. It will then describe the role that the selective nature of attention plays in achieving (or failing to achieve) awareness. A review is made of some of the experimental phenomena and techniques that have been used to examine visual awareness and the conditions under which it occurs. Particular focus is given to the visual masking paradigm and its associated phenomena. Masking has been found to be an effective and flexible method for manipulating awareness and for determining the conditions necessary for awareness to occur (Bachmann & Francis, 2014; Breitmeyer, 2014; Breitmeyer, 2015; Macknik, 2006). The primary focus of this thesis concerns a particular masking phenomenon known as Object Substitution Masking (OSM). OSM is of particular interest in the visual cognition literature because, unlike most traditional forms of masking, it seems to reflect, primarily, the operation of high level visual mechanisms (Di Lollo, Enns & Rensink, 2000). Towards the end of the chapter, the recent literature surrounding OSM will be evaluated and the aims of the current thesis in relation to that literature will be discussed.

1.1 Constraints of perceptual awareness

Over the past 25 years, the topic of human visual consciousness has become an area of legitimate scientific research and research interest (Breitmeyer, 2014). Visual consciousness as a concept has been argued to represent the phenomenal experience of human vision (O'Regan & Noë, 2001). In its most broad form it refers to one's ability to become aware of a scene, or elements within it (Eimer & Schlaghecken, 2002; O'Regan & Noë, 2001). However, the question of what visual consciousness and conscious visual experience is remains, arguably, one of the most intractable problems in cognitive science (Breitmeyer, 2014; Dehaene, Changeux, Naccache, Sackur & Sergent, 2006; Dennett, 1993; Koch & Tsuchiya, 2007; O'Regan & Noë, 2001). This is because the concept of visual consciousness remains not readily definable and currently has multiple meanings. Consequently, there is no clear consensus as to what any definition would look like (Breitmeyer, 2014; Dehaene et al., 2006). Recent research has attempted therefore to sidestep these issues by focusing on awareness as it occurs in specific types of information processing situations, rather than examining visual "consciousness" as a whole (Breitmeyer, 2015).

Visual awareness is most often equated to the internal spatial focus of attention. This fact was first demonstrated by Hermann von Helmholtz (von Helmholtz, 1867) and later emphasised by William James (1890). von Helmholtz asked observers to fixate at a location while looking "out of the corner of her/his eye" at a specified region in the visual periphery. Under these conditions it was found that the observer was able to report a letter that was presented at the peripheral location, but not a letter that was presented at the point of fixation despite the greater presumed visual acuity of the fovea (von Helmholtz, 1867).

Modern researchers have labelled this internal shift in attention the "attentional spotlight" (Lamme, 2003; Posner, Snyder & Davidson, 1980) or "attentional zoom lens" (Eriksen & James, 1986). More sophisticated experimental paradigms have been developed since the pioneering work of von Helmholtz (1867) to experimentally manipulate the focus of attention and explore the consequences for visual processing (Averbach and Coriell, 1961; Eriksen & James, 1986; Posner et al., 1980; Sperling, 1960). This research indicates that not all visual input which is encoding on the retina results in a pattern of neural activity which reaches the regions of the brain associated with visual awareness. Attending to a location seems to be a necessary condition for awareness (Lamme, Supèr, Landman, Roelfsema, & Spekreijse, 2000).

Attention is therefore a major element of this selective framework for awareness. Visual attention is a mechanism that allows relevant information to be selected or prioritised while largely ignoring irrelevant information (Chun & Wolfe, 2001). That is, visual attention works effectively as a "bottleneck" that allows certain visual information to be processed faster or deeper via the "attentional spotlight" while largely ignoring other information. This makes the attended information more readily available for action, memory or thought (Driver, 2001; Lamme, 2003; O'Regan and Nöe, 2001). This means that a large proportion of visual information processing is conducted prior to awareness of it being achieved (Breitmeyer, 2014; Breitmeyer, 2015). Attention alone does not seem sufficient to guarantee awareness however (Lamme, 2003). It can be argued therefore that it is important to understand the different types and levels of processing that occur and which enable and facilitate our awareness of visual information (Breitmeyer, 2014).

1.2 Experimental phenomena of visual awareness

The partial report paradigm (Sperling, 1960) was one of the first tasks to indicate a clear relationship between attention and awareness, at least in terms of an operational definition of awareness related to people being able to accurately report what they saw. From this point there have been numerous experimental phenomena which have been produced in the laboratory that demonstrate failures of awareness under a range of circumstances. These phenomena include change blindness, inattentional blindness, the attentional blink, continuous flash suppression, visual crowding, and visual masking.

1.2.1 Partial report investigations

Partial report investigations have been used to investigate how individuals become aware of information and how attention acts as a gatekeeper for awareness (Averbach & Coriell, 1961; Coltheart 1980; Desimone & Duncan, 1995; Sperling, 1960). They are used as a way of determining whether the observed limited span of perceptual awareness (Glanville & Dallenbach, 1929) is a consequence of limited short-term memory capacity or attentional capacity (Averbach & Coriell, 1961). Partial report studies typically require the participant to report about one specific aspect of a given display with trial to trial variation of what the participant will be required to report. This means that the participant is a-priori unaware of what they are required to report before any trial begins.

Sperling (1960) conducted the first partial report investigation. In this study participants were required to report a maximum of four letters that were briefly presented within a larger word grid. A maximum of 12 letters were presented within a grid three rows with four letters in each. After a 50ms presentation of the grid participants were asked to name a single row of letters based on a corresponding aural tone presented. As participants were not familiar with the letter strings or which row they would be asked to recall on each trial, this meant they would need to store the whole display in memory. Results were compared with a whole report condition in which participants had to report the entire content of the grid. It was found that partial report was always superior to whole report. That is, the average number of items reported in the whole report immediate memory test was 4.5 items whereas with the partial recall task recall was possible across the majority of the display (~9 out of 12 items). This demonstrates that the bottleneck for perceptual awareness (as measured by participants' report of the letters) was not related to memory resources but was rather attentional in nature. A further study examined the decay in reportable information by varying the time at which the signal tone was presented. It was found that consolidation of the stimuli was possible for extended periods of up to 250ms after the offset of the display. After this point there was no advantage for partial report over whole report for any row of letters.

Overall the pattern of results indicated that failures in awareness (in terms of the failure to report all the display items) are unrelated to memory storage capacity issues but are related to attentional factors. Sperling's (1960) work therefore indicates a distinction between pre-conscious visual representations (i.e. iconic memory) and conscious visual representations (i.e. visual short-term memory). The pre-conscious representation seems highly fragile and decays rapidly after stimulus offset. The conscious visual representation in contrast, seems to be more robust at holding information but is dependent on the directed focus of attention. It seems therefore that the act of attending to the stimuli allows transfer of the visual information into the conscious representation.

Averbach & Coriell (1961) followed on from this study using a modified version of Sperling's (1960) partial report paradigm. In their study a similar letter grid procedure was used, however a visual cue instead of an aural one was given to indicate the location in the grid to report. This method allowed more direct control of attention as attention was directed by the bottom-up capture that the cue provides. Two rows of

8 random letters were presented to the participant for 50ms. A single bar was presented above or below the letter for identification either 100ms prior to the stimulus array or up to 500ms after stimulus offset. The findings showed that memory of the stimulus array was maintained over long durations (post 200ms) while identification of the target letter prior to the stimulus onset still did not result in perfect performance. This suggests, as was found by Sperling (1960), that it is the number of items that require attention that limits awareness of (and the ability to report) the letter identities, rather than the actual storage of these items.

Averbach & Coriell (1961) conducted a second experiment involving what they called an "erasure" manipulation. The only difference in this experiment from the previous experiment was that the target identifier was a black outline ring that surrounded the letter of interest rather than a bar. In some respects the pattern of results in this experiment was similar to that of their Experiment 1. That is, when the ring identifier preceded the stimulus array or when it was presented at a short or long duration (i.e. 0-50ms; 200ms or more) after the stimulus array ability to identify the target remained somewhat intact. During medium intervals (of around 100ms) post-cue however the pattern of results differed quite dramatically to what was found with the line cue: here a sharp drop in performance was found. The results suggest that the further presentation of visual information surrounding the target location within a critical period has the effect of somehow disrupting the iconic percept of the target letter, preventing the transfer of that iconic percept into a stable object representation.

Taken together, these experiments were able to show that attention functions as a gatekeeper towards stable object perception and visual awareness of objects. Reporting of the stimuli is limited not primarily by memory capacity but rather the capacity of the attentional span. Furthermore, the results demonstrate the pre-attentive iconic representation of a stimulus is fragile and can under some circumstances be disrupted by the presentation of later stimuli, a point which will be discussed in relation to backward masking in section 1.3.

1.2.2 Change blindness

Change blindness (Rensink, O'Regan & Clark, 1997; Simons & Rensink, 2005) is the inability of observers to detect otherwise highly salient visual changes in a scene. The phenomenon tends to occur when the transients that normally alert an observer to the presence of a change are masked in some way. This masking of the transients is commonly produced by inserting a brief (e.g. 100ms) blank interval between the pre- (A) and post-change (A') version of the scene. In many demonstrations of change blindness the flicker paradigm is used. In this paradigm the sequence constantly cycles between the A and A' displays interleaved by the blank mask. This gives the appearance of a flicker as the scene is viewed (Rensink, et al., 1997; Simons & Levin, 1997). Under these conditions surprisingly large changes in the scene can often go undetected for many iterations of cycling displays. For example, it can take participants several seconds to notice the disappearance of a large building in the background (A') of a city scene (A) when the two scenes are presented within a flicker paradigm (Simons & Ambinder, 2005). In this situation, participants are most often aware that a change has taken place but are unable to identify the location of that change.

In these instances, the blank mask screen acts to produce a luminance change across the whole scene. Due to this widespread signal change, attention is distracted from the otherwise obvious change in the scene for prolonged periods (Simons & Ambinder, 2005; Simons & Rensink, 2005). Once this change in the scene has been discovered it becomes very obvious and unavoidable for the observer. This fact indicates that change blindness is not just a consequence of the difficulty in perceiving the change. Rather, it has been argued that the removal of bottom up transients that would otherwise guide attention to the change location is fundamental to change blindness occurring (Rensink et al., 1997; Simons & Ambinder, 2005; Simons & Rensink, 2005). Thus, in the absence of bottom up information, changes in the scene are not easily detected and are only perceived when the change location is spatially attended to.

Additionally, when the change is to a particularly salient or meaningful element of the scene, this change can be detected more rapidly (Rensink et al., 1997). Thus, it has been argued that change blindness reflects the necessity of focal attention to perceive changes (Rensink et al, 1997). Rensink's (2000a) coherence theory argues that the role of attention in change blindness is to create a coherent representation of the scene change. This is done by selectively holding a limited number of items from the original scene (A) in a short-term store. Focal attention then enables a coherent feedback between the items being held from the original scene and the new, low level items in the scene (A'). This feedback allows the object to retain a percept during brief temporal interruption and allows comparisons between the old and new displays to be made leading to the change being detected (Rensink, 2000b).

1.2.3 Inattentional blindness

Inattentional blindness (Mack & Rock, 1998), like change blindness, is another laboratory phenomenon which attests to the crucial role of attention in awareness. Inattentional blindness has many parallels with change blindness. Change blindness is the failure to notice an obvious change; inattentional blindness is the failure to notice the existence of an unexpected item, even where that item based on its feature characteristics should be easily identified (Jensen, Yao, Street, & Simons 2011). Inattentional blindness tends to occur when observers are engaged in some form of demanding visual task. For example when observers are asked to make a judgement about which of two arms (vertical or horizontal) of a fixation cross is longer a square suddenly appearing can go entirely undetected by the observer (Mack & Rock, 1998).

One of the most iconic examples of inattentional blindness was demonstrated by Simons & Chabris (1999). In this task observers were required to count the number of passes made between players wearing one colour while ignoring the passes made by those in another colour. During this sequence a gorilla would walk through the action. Once the display ended, participants were asked to record their count as well as whether they observed anything unusual (i.e. whether they had seen the gorilla). They showed that when observers were focused on performing a challenging perceptual task they missed the appearance of a gorilla walking through the scene (Simons & Chabris, 1999). Thus stimuli (e.g. the gorilla) can appear for several seconds and still remain completely undetected regardless of the fact these objects would be particularly salient in most circumstances (Moore, 2015; Most, Simons, Scholl, Jimenez, Clifford & Chablis, 2001). One suggestion is that there are little attentional resources available to detect the unexpected stimulus given the demanding, primary task (Most, 2010; Most, Scholl, Clifford & Simons, 2005).

Directed attention towards new information (e.g. a gorilla) therefore seems essential for awareness under conditions of high perceptual load (Cartwright-Finch & Lavie., 2007). Interestingly inattentional blindness is such a fundamental constraint that even expert perceivers still exhibit it even when viewing within their domain of expertise. Drew, Vö, & Wolfe (2013) found that more than three quarters of the radiographers in their study failed to notice the unexpected presence of a gorilla superimposed in one of a sequence of radiographic images they were examining.

1.2.4 Continuous flash suppression

Continuous flash suppression (CFS; Tsuchiya & Koch, 2005) is a phenomenon which occurs under conditions of dichoptic viewing (i.e. the presentation of different images to each eye). Separate images are presented to the two eyes: in one eye there is a rapid presentation of a constantly changing, high contrast sequence (usually of randomly generated patterns), in the other eye is the target stimulus which the observer has to report. When the target appears in synchrony with the flashing stimulus in the other eye awareness of the target stimulus is suppressed (Tsuchiya & Koch, 2005). These effects of CFS are often very strong and long lasting; the suppression of the target can occur for extended periods of up to a minute during which the target is not perceived and cannot be identified (Tsuchiyan & Koch, 2005). Research has shown that even though observers are unaware of the stimulus during CFS, certain stimulus categories such as faces and tools and the semantic content of these stimuli appear to still be encoded by the visual system (Yang & Blake, 2012). CFS has therefore been seen as a demonstration of the type of stimulus processing that occurs outside of awareness. Thus CFS – like change blindness and inattentional blindness – demonstrates that individuals can view visual stimuli, even for a sustained period, without showing awareness of them; it also suggests that quite extensive processing of a stimulus can occur even in the absence of awareness.

1.2.5 Attentional blink

The attentional blink (AB; Raymond, Shapiro & Arnell, 1992) is another phenomenon in which a stimulus does not reach awareness as a consequence of the task conditions under which it is viewed. The AB is a phenomenon in which the main variables of interest are typically temporal in nature (compared with the largely spatial, or inter-ocular nature of the interactions that occur in the earlier described phenomena). The AB occurs in the rapid serial visual presentation (RSVP) paradigm, one in which a sequence of visual stimuli are rapidly displayed in quick succession, typically at the same spatial location (usually fixation).

The AB tends to be observed under dual task conditions. In the AB there are typically two targets (T1, T2) which the observer has to detect and report from within the RSVP sequence. When these two targets are presented within 500ms of each other, reporting of T2 is greatly impaired even though T1 can usually be correctly reported (Raymond et al., 1992). When the two targets are separated by more than 500ms, reporting of T2 is found to be relatively unimpaired. Importantly when observers are instructed to ignore T1 while reporting T2 (single task conditions) accuracy in reporting T2 is typically high irrespective of the T1-T2 lag. This indicates that the phenomenon is a consequence of the additional task demands required for detecting the two targets. Thus the AB phenomenon suggests that attending to the first item somehow prevents awareness of the second item. It has been postulated that attending to T1 leaves little resources available to process T2 (Raymond et al., 1992) or that the AB represents an attentional dwell time in which the properties of T1 are being processed into a coherent perceptual representation (Duncan, Ward & Shapiro, 1994).

The AB -like partial report studies- therefore shows that the temporal order of visual information is vitally important to whether awareness of visual stimuli is achieved. This appears to be even more the case given that in the AB paradigm, T2 is typically not the last item in the sequence, with at least one item usually occurring after the T2. Research has shown that the presence of the subsequent letter(s) is in fact a necessary component of the AB paradigm (Giesbrecht & Di Lollo, 1998). This suggests that the AB not only requires the T1 to be attended to but also the T2 to be masked by the trailing stimulus in order for awareness to be prevented (Giesbrecht & Di Lollo, 1998). These findings indicate therefore that there are temporal limits for the deployment of selective attention (Dux & Marois, 2009).

1.2.6 Visual crowding

Visual crowding is another phenomenon used to explore visual awareness and the states in which it is prevented. With crowding perceptibility of the target is reduced when it is closely flanked by nearby distractors (Bouma, 1970). Crowding broadly refers to the deleterious effect of any surrounding (but not spatial overlapping) stimuli on the identification of a target (Gurnsey, Roddy & Chanab, 2011; Whitney & Levi, 2011). Crowding paradigms typical consist of a target stimulus (e.g. a letter) presented in the periphery surrounded by other stimuli of the same type (e.g. four letters) at varying distances (Bouma, 1970; Whitney & Levi, 2011). As such, crowding is a much simpler experimental paradigm than those mentioned in this section up to this point.

Crowding has a number of key hallmarks. One of these hallmarks is the *critical* spacing window. It was proposed by Bouma (1970) that the effect of crowding is relatively fixed and occurs only within a window of *0.5* of the targets eccentricity. Another hallmark of crowding is that it scales with target (and distractor) display eccentricity. That is, the distance at which distractors are expected to affect target perceptibility increases as the eccentricity of the display increases. The crowding phenomenon therefore shows that the close proximity of other stimuli can prevent awareness of it. This is particularly the case the further into the periphery the target is presented. One explanation for this effect is that the "attentional spotlight" is unable to focus narrowly enough on the target causing distractors to be attended to along with the target (Intriligator & Cavanagh, 2001). Visual crowding will be discussed in greater detail in Chapter 3.

1.2.7 Visual masking

Visual masking refers to the reduction in visibility (or awareness) caused to one stimulus (the target) by the presentation of a second stimulus (the mask) in close spatio-temporal proximity (Alpern, 1953; Breitmeyer, 2015; Breitmeyer & Ogman, 2000; Enns & Di Lollo, 2001; Michaels & Turvey, 1979). Visual masking is useful as a psychophysical tool for bringing performance within a measurable range and for allowing control over the duration available for a stimulus to be processed. Backward masks have been used to assist in the investigation of attentional capture, scene context, visual search, visual working memory, temporal attention, the time course of visual perception and even real world scene perception to name but a few (Castelhano & Heaven, 2011; Cosman & Vecera, 2011; Naccache, Blandin & Dehaene, 2002; Seidl-Rathkpf, Turk-Browne & Kastner, 2015; Vorberg, Mattler, Heinecke, Schmidt & Schwarzbach, 2003). Visual masking is also deemed interesting in its own right for the information it provides about the nature of visual processing and conditions for awareness (Bachmann, 1994; Breitmeyer & Ogman, 2000). There is a long tradition of research on visual masking in psychophysics and the phenomenon in its basic form has been known about since the 19th century (Breitmeyer & Ganz, 1976; Breitmeyer & Ogman, 2000; Enns & Di Lollo, 2000; Kahneman, 1968).

A general distinction can be made between two types of masking: forward and backward. This distinction concerns the temporal position of the mask with respect to the target. Forward masking refers to the reduction in visibility of a target produced by a mask that is presented prior to the target's onset while backward masking relates to visibility impairments caused by a mask that follows the target in time (Breitmeyer & Ganz, 1976).

Visual masking paradigms, like crowding paradigms, tend to be rather less elaborate in terms of the stimulus presentation sequence than some of the earlier described phenomena; indeed a basic masking effect can be produced with the presentation of just two stimuli in sequence. As visual masking forms the basis of this thesis it will be discussed in more detail in section 1.3.

1.2.8 Summary

Together these phenomena attest to the limited conscious representations that observers seem to have when viewing static or dynamic scenes. These phenomena have been used to show that what individuals become aware of is, at any given moment, only a small proportion of the visual information available on the retina. It seems much of what the eyes "see" fails to reach awareness. Moreover, study of these phenomena, among others, has been claimed to indicate something about the nature and capacity of attention selection. This is particularly in relation to its apparent selective process (e.g. Lamme, 2003; Rensink, 2002), along with some of its temporal characteristics (Dux & Marois, 2009; Kristjansson & Nakayama, 2002).

1.3 Visual masking

Visual masking has been seen as another example of how attentional processing of visual stimuli can prevent stimuli reaching awareness. Visual masking has been of particular research interest because of its potential to inform about the spatiotemporal properties of information processing, and specifically, pattern-forming operations within the visual system (Breitmeyer & Ganz, 1976). Backward masking in particular has also garnered considerable research interest because of the seemingly counterintuitive nature of a backward mask to have a clear effect on the perceptibility of a target (Bachmann, 1994; Breitmeyer, 2015; Breitmeyer & Ogman, 2000).

Visual masking was first reported by Baxt (1871/1982). It was demonstrated that the presentation of a brief stimulus in close spatio-temporal proximity to a previously presented stimulus reduces the perceptibility of the first stimulus (Baxt, 1871). Baxt was interested in the question of the formation of a conscious percept. It was, and largely still is, thought that masking could be used as a tool for understanding how long it takes for visual information to reach awareness, and the relationship between attention and awareness (Baxt, 1871, see Goodhew, Pratt & Dux 2013; Breitmeyer & Ogman, 2000).

Backward masking has also been regarded as a useful way of inferring understanding about visual processing. It has been used to investigate the temporal order of visual information, how information is processed through the various levels of the visual system and to examine and measure visual awareness (Bachmann, 1997; Breitmeyer & Ogman, 2000). It has also been argued that models of backward masking could potentially enhance understanding of numerous other spatiotemporal phenomena including visual persistence and temporal order discrimination (Breitmeyer, Hoar, Randall & Conte, 1984; Breitmeyer & Ogman, 2000).

1.3.1 Types of backward masking

It has classically been assumed that there are four distinct types of traditional backward masking: masking by light; masking by structure; noise masking and metacontrast masking. One of the simplest forms of masking is *masking by light* (Crawford, 1947). This form of masking is not dissimilar to the blank mask presented in the flicker change blindness paradigm described in section 1.2.2. Backward masking by light occurs when a large and uniform, spatially overlapping flash of light is presented in a short time frame after the presentation of a brief target. *Masking by structure* (or pattern masking; Turvey, 1973) refers to the involvement of spatial superposition of contours. Masking by structure requires the mask to be structurally related to the target in order for effective masking to occur (e.g. orientation, structure or other figural features; Breitmeyer & Ganz, 1976). For example, a target letter *T* would experience strong masking when presented with a mask of cluttered overlapping letters (Breitmeyer & Ganz, 1976).

Noise masking (Kinsbourne & Warrington, 1962) involves the use of random dot patterns that spatially overlap the target. In this situation the mask and target bear no structural relation with one another. The mask acts to confuse rather than eradicate perception of the target (Breitmeyer, 2015). For example, when a pattern of random dots follows the presence of a target letter *T*, identification of the target is expected to be greatly impaired (Breitmeyer & Ganz, 1976). The final type of masking in the classical taxonomy is *metacontrast masking* (Alpern, 1953). A more detailed description of metacontrast masking is given in the section below.

Metacontrast masking

Metacontrast masking is arguably fundamentally different to other forms of masking because the mask surrounds the target rather than spatially overlapping it. Metacontrast is also different from other masking forms in terms of the temporal properties it typically exhibits. The other three traditional forms of masking tend to produce what is called a Type A masking function whereby the magnitude of the masking function decreases monotonically with increasing stimulus onset asynchrony (SOA). In contrast metacontrast masking typically produces what is referred to as Type B masking. Type B masking effects vary in magnitude in a nonmonotonic, U-shaped fashion i.e. masking is most evident at intermediate SOAs (e.g. 50ms to 100ms); minimal masking is found when the SOAs are shorter or longer than this (Bachmann, 1994; Breitmeyer & Ogman, 2000; Enns & Di Lollo, 2000).

Metacontrast masking occurs when the target and mask have closely abutting contours that do not spatially overlap. The spatially adjacent mask works to suppress information relating to the target presumably by a process of inhibiting the contours (Breitmeyer & Ganz, 1976). The mask is commonly an outline shape of the target e.g. a disk surrounded by an annulus in which the inner contour of the annulus closely abuts that of the disk. With a disk as a target, perceptibility is often assessed by use of a subjective rating scale or apparent brightness measure. For example, in these paradigms a filled disk is presented for around 30ms, after a varied SOA an annulus is then presented surrounding the location where the target was presented for 30ms. Participants are required to subjectively rate their confidence of whether a target was present. Detection of the target in these instances is worst with an SOA at around 50ms (Bruchmann, Breitmeyer & Pantev, 2010; Bruchmann, Hintze & Mota, 2011). Other metacontrast studies have used a forced choice measure where, for instance, a Landolt C target is used (closely flanked by a surrounding ring mask) and observers have to report the gap position of the target (e.g. Tata, 2002).

Metacontrast masking appears to be vitally dependent on the close proximity between the outer contours of the target and inner contours of the mask (typically within 0.12° of visual angle; Tata, 2002). When the contour separation is increased by even the smallest of a degree, masking is markedly reduced. This masking effect is thought to take place as the result of inhibitory interaction between neurons that represent the target and mask (Breitmeyer & Ogman, 2000; Enns & Di Lollo, 2000).

1.3.2 Masking processes

Classical theories of masking have tended to posit the existence of two different masking processes, *integration* and *interruption* (Breitmeyer & Ogman, 2000; Breitmeyer & Ogman, 2006). These two processes were argued to relate directly to, respectively, the type A and B masking functions described in section 1.3.1.

Type A (integration) masking effects are argued to occur early in the visual processing stream. They are the result of the target and mask being perceived as part of the same pattern rather than as two separate patterns. Integration masking is said to be most effective with SOAs close to 0ms whereas little masking is expected to occur with SOAs of 100ms pre or post target. This is conceivably because of poor temporal resolution in the visual system (Breitmeyer & Ganz, 1976; Breitmeyer & Ogman, 2000).

Type B interruption masking effects occur when processing of the target is interrupted by the onset of the mask at a close spatial location. Interruption masking, unlike integration, is argued to involve competition between the target and mask at higher level –and later stage– object recognition mechanisms. Unlike integration effects, interruption effects are minimal when the SOA is short and most effective at intermediate SOAs (Breitmeyer, 2015; Breitmeyer & Ganz, 1976; Breitmeyer & Ogman, 2000).

The distinction between integration and interruption masking has been found as a useful framework for understanding the characteristics of masking produced by masks with small or large asynchronies in onset (Breitmeyer & Ogman, 2000). The sorts of factors that are important in masking under these different conditions seem to reflect the processing levels at which they occur. For instance integration masking is strongly affected by physical factors (e.g. the relative energies or feature similarity of the target and mask) while interruption masking is affected by informational factors (Enns & Di Lollo, 2000). For example integration masking is affected by mask luminance manipulations in line with it reflecting interactions occurring at an early processing stage. Thus a brighter mask is more easily integrated with and dominates over the target in the resulting fused percept producing more masking (Enns & Di Lollo, 2000; Scheerer, 1973).

Interruption masking, by comparison, does not appear to be particularly affected by luminance contrast; instead the critical factor seems to be the presentation of new visual information (i.e. the mask onset; Bachmann, 1994; Breitmeyer & Ganz, 1976; Breitmeyer & Ogman, 2000; Enns & Di Lollo, 2000; Scheerer, 1973). This means that the backward mask can interrupt processing of the target when the mask onsets after the target. Consequently, instead of the target being processed, the visual system will begin processing the newly appeared stimulus (i.e. the mask) leading to interruption of target identification (Coltheart & Arthur, 1972).

These proposed processing differences have been seen as a useful way of distinguishing between types of masking. That is, based on the type of masking effect that is exhibited (integration or interruption), it can be estimated whether the exhibited masking function was the consequence of early or later processing impairment. Equally, these proposed processing differences have been beneficial in understanding the clear differences in masking effects.

1.3.3 Models and theories of backward masking

There have been numerous models of masking produced over the last few decades. One of the most influential models is that of Breitmeyer and Ganz (1976) which put a central focus on the difference between transient and sustained processing channels in the visual system and how this contributes to the masking effects produced.

Breitmeyer & Ganz (1976) sustained-transient dual-channel account of backward masking

The model by Breitmeyer & Ganz (1976) presented a neurophysiological approach to masking. This model is based on the functional and organisational features of the visual system. Specifically it is grounded in the knowledge that visual pathways are hierarchically organised; and that the visual system contains both inhibitory and excitatory processes (Breitmeyer & Ganz, 1976). Within the visual system there are two major cell channels that selectively process different visual stimulus elements: magnocellular (M) and parvocellular (P). M cells have low spatial frequency compared to P cells but greater temporal sensitivity and conduction speeds. M cells are therefore more sensitive to transient stimulation such as stimulus onsets, offsets, and motion while P cells are more sensitive to slow moving or stationary stimuli (Breitmeyer & Ganz, 1976; Legge, 1978).

It is argued that P cell channels underlie conscious awareness and object identification. M cell channels also influence this awareness either by enhancing or suppressing certain object representations (Breitmeyer & Ganz, 1976; Goodale & Milner, 1992; Goodhew, Boal & Edwards, 2014; Milner & Goodale, 2008). The model by Breitmeyer & Ganz (1976) relates masking to this physiological evidence of interactions between M (transient) & P (sustained) cell channels. This model is therefore based on a number of assumptions regarding the nature of these visual channels. Firstly, slow processed information relating to object features such as brightness, colour, figural detail and pattern information require sustained, P cell processing channels. Fast, spatially coarse pattern processing such as contour is processed through transient, M cell channels. These transient channels are also required for the signalling of a spatial location and/or for target location changes (e.g. visual motion).

Within this model backward masking is explained due to inhibition of the sustained target channel by the transient mask channel (Breitmeyer & Ganz, 1976; Breitmeyer & Ogman, 2000). Integration masking, in this model, is therefore caused by the prolonged mask presentation. Response indicators such as form-detection and luminance discrimination produce sustained (P cell) activation whereas the trailing mask onset causes transient (M cell) activation (Breitmeyer & Ganz, 1976; Kahneman, 1964; Kline & Schieber, 1981; Kulikowski & Tolhurst, 1973). The temporal differences of these streams result in an integrated percept of the target and mask stimuli.

In the transient-sustained model interruption masking is argued to occur as a consequence of the temporal gap between the onsets of target and mask. The faster, transient channel is activated both by onsets and offsets (e.g. the mask); which in turn suppresses the slower, sustained channel containing target information (Breitmeyer & Ganz, 1976; Breitmeyer & Ogman, 2000). The target activity in the sustained channel is inhibited by the faster, transient mask activity when the mask onsets 50-100ms after the target. With SOAs of under 50ms the target-related sustained response is yet to be reached meaning the transient mask activity cannot interfere with it. With SOAs of 100ms and longer the target-related sustained response has already been consolidated meaning that masking cannot occur (Breitmeyer, 1980; Breitmeyer & Ogman, 1976; Tata, 2002).

The perceptual retouch theory of visual masking

The perceptual retouch (PR) theory of visual masking was introduced by Bachmann (1984; 1994). The PR theory aims to explain masking in terms of the temporal sequence of stimuli and the interactions that are posited to take place between these stimuli during rapid temporal presentation (Bachmann, 1994; Kirt & Bachmann, 2013). Specifically, PR can explain how the backward mask dominates and potentially overwrites the target in conscious perception.

This model is based on the interaction of known mechanisms that enable the conscious experience of visual information and focuses on the interactive activity between anatomically distinct pathways (Breitmeyer & Ogman, 2000; Kirt & Bachmann, 2013). That is, conscious perception occurs as the result of cortical neuronal activity that encodes environmental features embedded in the relevant receptive field. These neurons relay content based on presynaptic input from specific relay nuclei (including lateral geniculate nucleus). This process binds the “contents of subjective experience” such as colour, orientation, spatial frequency and edge location into a specific, identifiable perceptual object (Bachmann, 1994; Breitmeyer & Ogman, 2000; Kirt & Bachmann, 2013).

In order for these contents to then reach subjective conscious experience, according to the theory, two requirements must be met within the visual system for modulation to occur. Firstly, the initial network must contain enough non-specialised spontaneous activity for the neural computations required for conscious experience to take place. Secondly, the specific cortical activity requires sufficient modulation by the presynaptic input produced by the ascending reticulo-thalamic system (Kirt & Bachmann, 2013).

This modulation system has three important properties that enable the subjective experience of a stimulus to result. Firstly, activity within this system does not actually contain information about perceptual content. Secondly, when an activity surge is caused by non-specific sensory input, it has an effect on the cortical neurons which occur at a longer temporal delay than those of the first responses to the sensory information at the specific cortical neurons. Specific cortical responses emerge between 40 and 100ms whereas the non-specific cortical responses emerge between 100 and 150ms. Thirdly, it is expected that non-specific receptive fields are larger than specific receptive fields (Bachmann, 1994; Kirt & Bachmann, 2013).

Within the PR model therefore, backward masking occurs as a consequence of a misbinding of the specific mask representation with the awareness generating, non-specific activity of the target. That is, the non-specific (target) responses take longer to reach cortical level processing than the specific (mask) responses due to the slower processing in the non-specific receptive fields. This means that the initiated target and optimised mask responses coincide in cortical processing. Consequently, the cortical specific response to the target is more decayed than that of the mask at the point that the nonspecific modulation signals arrive at the pre-synaptic cortical specific pyramidal neurons. In these instances, the mask percept is argued to overpower that of the target (Bachmann, 1994; Kirt & Bachmann, 2013). This means that activity leading to visibility of the target will be heavily suppressed whereas the mask activity will be enhanced. This results in the mask alone becoming the object which emerges in awareness.

1.3.4 Summary

There are two types of visual masking with which a distinction is commonly made: those being forward and backward masking. Backward masking generally garners more research interest and is viewed as more theoretically interesting as this type of masking shows the ability of visual information presented after the target to disrupt awareness of it. Within backward masking there are four common types of masking that can be differentiated from one another with metacontrast masking appearing the most phenomenally interesting. This is because metacontrast masking exhibits what is refers to as a Type B, nonmonotonic U-shaped masking function associated with interruption processes. In contrast, the other types of masking (light, structure and noise) exhibit Type A masking functions associated with integration processes.

Numerous models have been produced in the aim of explaining such masking phenomena. Models such as Breitmeyer & Ganz's (1976) sustained-transient dual-channel account and the perceptual retouch theory are perhaps two of the most comprehensive classical models of traditional backward masking. The models are classical because they assume that masking occurs largely as a consequence of interactions early in the visual system. They also assume that the relevant processes are essentially feedforward in nature. These models have largely used a neurophysiological approach to explain masking. That is, these models have focused on the functional and organisational hierarchical structure of the visual system to explain both Type A and Type B forms of masking.

1.4 Object Substitution Masking

Object substitution masking, also commonly referred to as common onset or four-dot masking, is a recently discovered form of masking (Di Lollo et al., 2000; Enns & Di Lollo, 1997). It has a set of properties which seem to set it apart from traditional forms of backward masking. It has therefore been argued that OSM cannot be explained by existing theories of masking (Di Lollo et al., 2000; Enns, 2004; Enns & Di Lollo, 2000). In OSM, a sparse surrounding mask which commonly consists of no more than four dots that do not spatially overlap the target can act as a mask. That is, when all display items offset together little to no OSM is found. In contrast when the four dot mask (4DM) remains on the screen after the target disappears, for as briefly as 60ms after target offset, the perceptibility of the target is markedly impaired (Di Lollo et al., 2000; Enns & Di Lollo, 2000).

OSM was argued by Di Lollo and colleagues (2000) to differ fundamentally from other forms of masking in a number of key ways.

OSM, unlike metacontrast masking, was argued to have little impact when the target is presented alone in the display or when the target differs from distractor items on at least one distinctive feature (e.g. colour; Di Lollo et al, 2000; Lleras & Moore, 2003; Moore & Lleras, 2005). Furthermore OSM does not occur when the mask's onset precedes the target in addition to trailing its offset (Di Lollo et al., 2000; Goodhew, Dux, Lipp & Visser, 2012; Lleras & Moore, 2003). OSM, in contrast to other forms of backward masking such as pattern and metacontrast, requires only a sparse trailing mask (the 4DM) which does not need to spatially overlap the target location or even have contours adjacent to it. Di Lollo and colleagues found that masking by OSM was equally effective in reducing target perceptibility with the use of a ring or 4DM.

Furthermore, the time in which the mask trails the target appears to be important for masking to occur as opposed to the SOA between the target and mask (Di Lollo et al., 2000; Enns & Di Lollo, 2001). In particular the onset time of the mask in relation to the target (described in terms of the SOA) does not seem to be a particularly critical variable for OSM (Di Lollo et al., 2000). It seems that the length of time that the trailing mask continues to be displayed for is more vital for OSM (Di Lollo et al, 2000; cf. Enns, 2004; cf. Jannati, Spalek & Di Lollo, 2013). OSM has also been argued to be a more effective way of measuring awareness to visual stimuli than other forms of masking (Goodhew et al., 2013). It is proposed that OSM selectively impairs awareness for a specific stimulus without producing large image-level degradation of the form seen in pattern or noise masking for example (Goodhew et al, 2013).

A feature of OSM that seems to make it particularly distinct from other forms of masking phenomena is that it is argued to be critically dependent on the focus of spatial attention (Di Lollo et al., 2000). Consequently, it is argued that OSM fits poorly into classical masking theories (Enns & Di Lollo, 2000). Enns & Di Lollo (2000) proposed that attention is an integral and essential component in OSM. That is, in OSM little masking is found when attention can be rapidly drawn towards the target location whereas strong masking occurs when attention towards the target is delayed (Di Lollo et al., 2000). Existing models of masking are therefore argued to be inadequate as they fail to account for such attentional processing. Furthermore, Di Lollo and colleagues (2000) proposed that interactions which occur in re-entrant processing underlie OSM and are critical in its occurrence. That is, the mismatch between high level codes and low level activity is central to OSM; this potential for re-entrant communication is an additional factor that fails to be accounted for by standard masking theories. As such, the Object Substitution Theory of Masking (OSTM) was developed as a robust way of explaining OSM, accounting for the numerous factors that fail to be accounted for in traditional masking theories.

1.4.1 Re-entrant processing

The OSTM is a neurocognitive theory of masking and, more generally, of perceptual processing. The OSTM was inspired by neurophysiological observations about the visual system which have shown that communication between brain areas is seldom unidirectional but rather bidirectional (Zeki, 1993). Since the 1990s onwards, there has been a general acceptance in the literature that pathways in the visual cortex are bidirectional (Enns, Lleras & Di Lollo, 2006; Felleman & Van Essen, 1991; Zeki, 1993). Felleman & Van Essen (1991) found that the primate visual cortex consists of 32 brain areas with 305 connections. This includes 25 neocortical brain areas that are exclusively or predominantly visual in function; in addition to 7 visual-associated areas. Within this model there exists a visual hierarchy containing 10 levels of visual cortical processing. This hierarchy features numerous intertwined processing streams between low level areas such as V1 and V2 and high level areas in the temporal and parietal lobes (Felleman & Van Essen, 1991). This bi-directionality means that signals sent from early visual cortex (V1) to higher visual locations receive signals back from those higher level areas through re-entrant pathways (Damasio, 1994).

Research has shown important spatial resolution differences between lower and higher processing areas in the visual cortex. The primary visual cortex (V1) contains the smallest receptive field (0.5–2° of visual angle, the smallest receptive field sizes being those in the fovea, the largest being those in the far periphery of the visual field). In the extrastriate areas (e.g. V4) receptive fields are around four times greater in size, ~2-8° (Desimone & Schein, 1987). In area IT (infero-temporal cortex) receptive fields are very large (around 30° of visual angle). Thus receptive field size seems to increase progressively as visual information progresses from lower to higher processing areas.

This means that cells lower down in the visual hierarchy (V1) have receptive field units which are highly spatially local in their response properties. They have no information which allows the cell to distinguish whether the external visual stimulus (e.g. a vertical line) is an isolated element or part of a more complex configuration (e.g. the nearest edge of a cube). In contrast, receptive field units higher in the visual cortex, because they receive input from a broad range of the visual field, can be responsive to the entire object (Allman, Miezin & McGuinness, 1985; Cottaris & De Valois, 1998; Lamme & Roelfsema, 2000; Riesenhuber & Poggio, 1999). Thus it is only through comparison between the response properties of cells in different levels of the visual system that the brain can both identify a viewed stimulus and determine its location in space. One way that this can be achieved is through iterative exchanges between the different levels of the visual system (Felleman & Van Essen, 1991; Lamme & Roelfsema, 2000; Zeki, 1993).

This information exchange can occur by way of feedforward or feedback processing. The feedforward processing stream occurs when information processed early in the processing stream (e.g. V1) causes activation of successive levels within the visual processing hierarchy through a cascade of feedforward connections (Lamme & Roelfsema, 2000). This feedforward processing sweep has been argued to reach its highest level of processing within around 100ms of stimulus onset. Once this feedforward sweep has taken place, the neurons involved remain active throughout the hierarchy. At longer latencies (i.e. post 100ms) feedback (re-entrant) responses from higher hierarchical locations can be incorporated into processing (Lamme & Roelfsema, 2000). This re-entrant processing activity is necessary to refine details of the stimulus and stimulus representations while also enabling them to become accessible to visual awareness (Goodhew et al., 2013; Lamme & Roelfsema, 2000). Re-entrant processing can therefore lead to a full perceptual identification of the stimulus (Damasio, 1994; Di Lollo et al., 2000).

1.4.2 The Object Substitution Theory of Masking

The central assumption of the OSTM is that visual perception is based on the re-entrant exchanges between multiple modules located over the visual field (as discussed in section 1.4.1). It is only when a successful match is made (of the target) between the higher and lower level processing that conscious perception is achieved (Di Lollo et al., 2000).

The OSTM sets OSM within the re-entrant processing framework. This theory in essence argues that OSM is the consequence of the inherent sluggishness of the visual system in responding to rapid visual input. This sluggishness is caused by the need for interactive processing between low level signals and high level codes. That is, representations at the input level do not, by themselves, result in awareness. For awareness to occur the current input representation has to be successfully matched with the (delayed) re-entrant signal. Consequently, under conditions of rapid changing input the visual system can fail to form a conscious percept of stimuli (Di Lollo et al., 2000).

The different conditions in the standard OSM paradigm can be understood as follows. In the unmasked condition, when the target and mask onset and offset together the target is usually easily identified. According to the OSTM under these conditions the signals from the ongoing low level activity and the high level, re-entrant codes match causing no imbalance in the module (the representation of the target is consistent across the processing levels; Di Lollo et al., 2000; Enns & Di Lollo, 2000).

The difficulty for the visual system occurs when the mask lingers on screen after the target has disappeared. Here the ongoing low level activity and the high level re-entrant signal (based on an earlier feedforward sweep) will be mismatched due to the temporal differences between feedforward and feedback processing. In these conditions the low level, ongoing activity provides strong retinal input relating to the 4DM alone with only fading input related to the target. This means that there will be a mismatch between the current input signal (i.e. 4DM) and the re-entrant information received from high level codes (i.e. target+4DM; Di Lollo et al., 2000; see Figure 1).

Under these circumstances, the re-entrant signal has a low correlation with the input level representation. This means that the initial hypothesis containing the target is likely to be rejected. A new iterative cycle will then be initiated based on current input in an attempt to find a match between the re-entrant signals and the current input. In these instances the outcome of the process tends to be biased towards a perception of the mask alone; the longer the mask lingers, the higher the likelihood of this occurring. If few iterations are required (e.g. if attention can be quickly drawn to the target), information relating to the target may still exist at the input level activity which will lead to awareness of the target (Di Lollo et al., 2000).

Conversely when a large number of iterations are required, the likelihood of target related activity still existing in the low level activity is greatly reduced. In these instances, a new perceptual hypothesis is formed consistent with the ongoing low level activity of the mask alone. This leads to a new percept of the mask alone replacing the percept of the target+mask. Consequently, awareness of the target is not achieved. This process is viewed as a perceptual substitution of the target+mask percept by the mask alone percept. This perceptual substitution by the mask results in OSM according to the OSTM (Di Lollo et al., 2000).

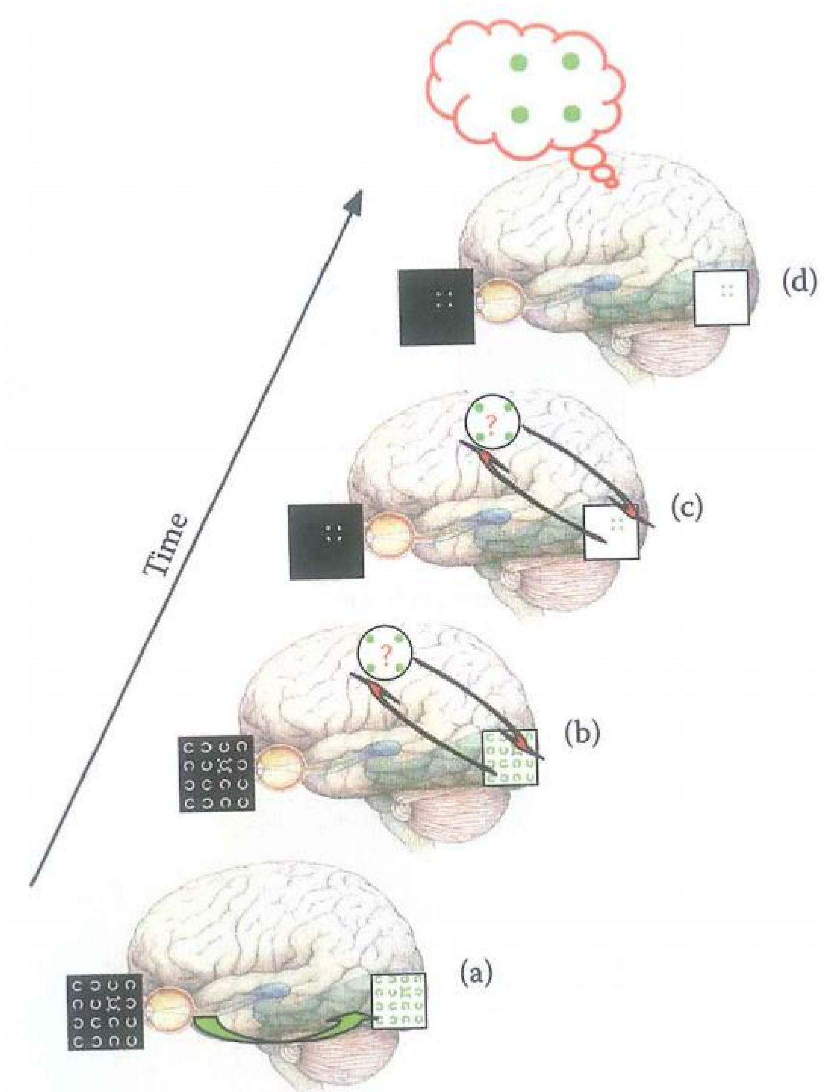

Figure 1| Schematic representation of the re-entrant processing sequence of events involved in object substitution masking (from Di Lollo, 2010, Figure 2.9; page 33).

Another key element for OSM is spatial attention. Spatial attention is intrinsically linked to OSM according to the OSTM. This is accounted for within the model's re-entrant framework. When spatial attention is not focused on the target; either because it is focused at a different location or is distributed across multiple items within the visual field, the target is argued to be more vulnerable to OSM (Di Lollo et al., 2000). This spread of attention means that the representation of the target in high level codes is not strongly formed. This spatial attention factor in OSM is classified as *time to contact* in the Computational Model of Object Substitution (CMOS), a formal mathematical implementation of the OSTM presented by Di Lollo et al (2000).

Spatial attention can be experimentally manipulated in a number of ways. Di Lollo et al (2000) presented evidence for the consequences of two different forms of spatial attention manipulation: display set size and spatial pre-cueing. Set size is an attentional variable which causes reductions in performance. As set size increases (for example from a display of 1 stimulus to 16 stimuli) performance in conjunctive visual search tasks dramatically decreases while reaction times incrementally increase (Palmer, 1994; Treisman & Gelade, 1980). In OSM, the effect of set size is thought to increase the number of iterations required to identify the target; and in doing so increases the strength of OSM (Di Lollo et al, 2000). This means that when the target is the sole item on the screen (set size 1), spatial attention can be quickly deployed to it, regardless of its random display location. However, when there are multiple distractors displayed with the target, the iterative process becomes longer and attention will be deployed to the target more slowly. Thus, accuracy decreases with increasing set size under these conditions.

This also results in a more intensive iterative process and weakened processing of the target+mask percept compared to when the target is presented alone. In trials when all elements onset and offset together, a standard set size effect is expected with increasing set size e.g. an overall reduction in performance. However when the mask continues in isolation, set size is also expected to have a progressively larger effect with increasing mask duration, as was found by Di Lollo and colleagues (2000; see Figure 2). This is due to re-entrant processing and the increased number of iterations required to process the target (Di Lollo et al., 2000). The set size effect is therefore predicted to be substantially larger during masked conditions (asynchronous offset) than in unmasked conditions. As such, attention is modelled as a linear function of set size in the OSTM. The time taken to reach the target and make comparisons based on it is assumed to increase linearly with set size (Di Lollo et al., 2000). Under the OSTM OSM is thus caused by the combined increase in mask duration and set size.

Di Lollo and colleagues (2000) also used spatial precuing to examine the role of attention in OSM. Spatial precues allow attention to be prefocused on the target location meaning the effect of OSM should be substantially diminished (Di Lollo et al., 2000). The 4DM was used to cue the target and would appear alone prior to or after the stimulus display for varied durations. Precuing of the target led to substantial reductions in OSM across all set sizes; the influence of OSM reduced incrementally with the duration of the leading precue. The precue thus acted to quickly draw attention towards the target location preventing effective masking.

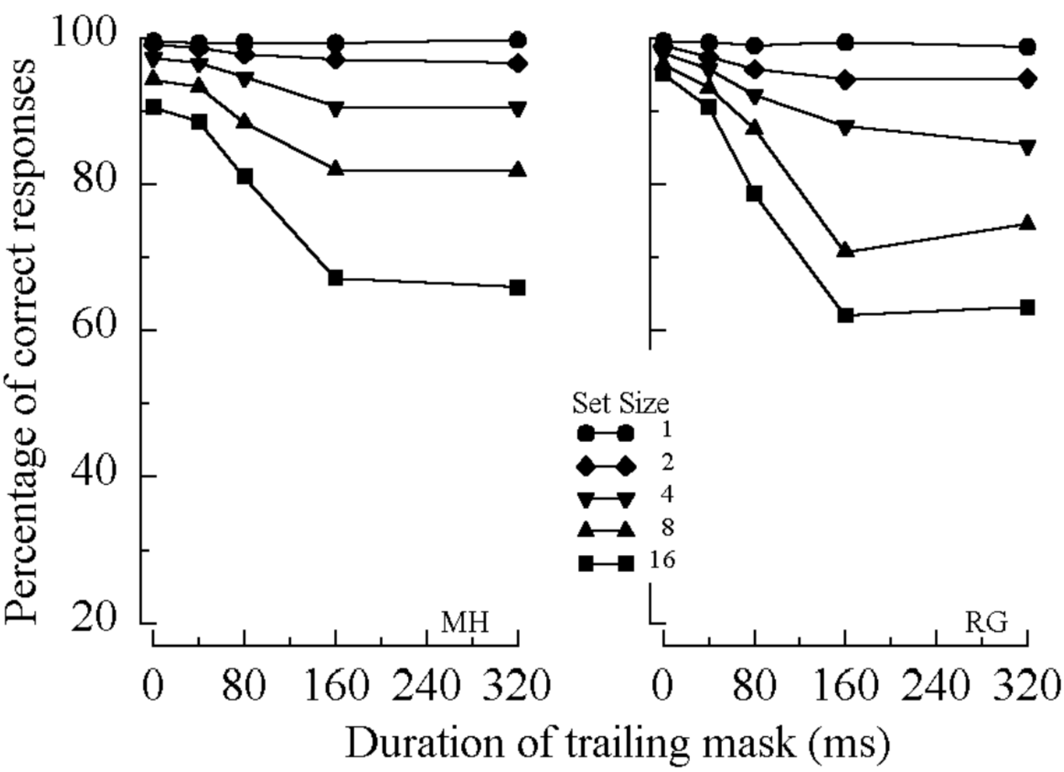

Figure 2| Performance in Experiment 3 of Di Lollo and colleagues' (2000; Figure 6, Page 491) initial reporting on OSM.

1.4.3 Object Updating theory of OSM

The object updating theory (OUT) is a different account of OSM to the OSTM. The OUT was initially proposed by Lleras and Moore (2003) and elaborated in greater detail in Moore and Lleras (2005). The OUT is perhaps better thought of as a development of the original OSTM than as a competing theory. The theories share many of the same underlying assumptions. The OUT, like the OSTM, assumes that at the neural level re-entrant processes underpin both normal perception and masking. Also like the OSTM the OUT assumes that OSM is affected by mask duration and the allocation of attention.

The OUT departs from the OSTM largely in terms of the assumption made about the manner in which the target and mask are represented by the visual system and in terms of how this results in masking. The OUT emphasises the sorts of processes that occur at the level of *object-token* representations during OSM. Object tokens are spatiotemporal representations of the presence of an object. These object tokens are updated over time to maintain a stable representation of an object throughout transformations of its retinal image (Kanwisher, 1987; Lleras & Moore, 2003; Treisman & Kanwisher, 1998).

The OUT argues that OSM occurs as the consequence of the target and mask stimuli being encoded by the visual system with a single object-token representation, rather than with two separate object tokens. In these instances, the representation of the target+mask is expected to update to represent the mask alone (when the mask offsets asynchronously) obscuring target awareness (Goodhew et al., 2013). To explain, in a standard OSM paradigm the target (with the surrounding 4DM as its identifier) is presented for a brief period (e.g. 40ms). When this 4DM continues to be displayed without the target for a prolonged period (e.g. 180ms) substantial masking occurs. Under these circumstances the single object token representation containing information about the target and mask updates to contain information about the mask alone (Lleras & Moore, 2003; Moore & Lleras, 2005). This means that the target and mask are treated as a single object; with the space inside the four dots (including the target) treated as part of that same object.

In addition to the proposed role of object-tokens, the OUT also assumes a role for attention. It proposes that attention must be allocated directly to the trailing mask for successful masking to occur. This means in addition to the target being protected from masking when it is sufficiently attended to, it is also protected when the trailing mask is not attended to (Lleras & Moore, 2003). Within this model therefore masking will only occur when the conditions of presentation mean that the target and mask become represented with a single object-token. Where this occurs, information relating to the mask alone will overwrite information about the target. However, when the mask and target are individuated as separate objects (e.g. when presented at distant locations in the absence of perceived motion connecting the two, or when the two share perceptibly different onsets), information relating to the target will not be overwritten (as long as the target is attended to) and OSM will not occur (Gellatly, Pilling, Carter & Guest, 2010; Lleras & Moore, 2003; Moore & Lleras, 2005; Pilling & Gellatly, 2010).

Lleras & Moore (2003) examined the role of these object-token representations in OSM in terms of spatial dynamics. Unlike with most OSM experiments, the 4DM was not used to inform the target location; target and mask locations were independent of one another. They found that OSM is dependent on the target and mask being represented as one object, as predicted by the OUT, as mask location was found to have a significant effect on performance. Strong masking was found when the target and mask were presented at the same location whereas little masking was found when they were presented independently. This suggests that the mask must first cue the target in order to later mask it.

Lleras & Moore (2003) also examined the effect of target and mask representations in OSM using apparent motion. In these instances the 4DM surrounded the target at onset but appeared in a different location after one of a number of inter-stimulus intervals (ISIs). At short ISIs, masking magnitude was comparable to a standard delayed mask offset; no significant effect of masking was found for the long ISIs however. This same pattern of results was reproduced even when the mask comprised of no more than a single dot. This was explained as the mask (single object-token) being perceived as moving position at the short ISI while at the long ISI it was viewed as a new instantiation (separate object-token). The long ISI, according to the OUT, provides adequate time between the target+mask display and the mask alone display to separate the object-token representations.

Pilling and Gellatly (2010) further examined the use of object-token representations in OSM using apparent motion. In addition to the apparent motion paradigm developed by Lleras and Moore (2003), Pilling and Gellatly included a condition in which dots identical to the masks were presented in the periphery of the display prior to stimulus onset. Under the same conditions as Lleras and Moore, substantial OSM was produced as expected. However when the peripheral dots were included in the display, masking was largely attenuated. This was argued to be because the peripheral dots offset with the target array. The fact that they offset this way led to a perception of connecting apparent motion between the peripheral dots and masks (rather than between the target array and mask). This meant that the target was more easily individuated from the mask as a separate perceptual object.

Moore & Lleras (2005) attempted to further investigate conditions in which the perception of target and mask as the same or separate objects was manipulated. When the mask moved or jiggled independently of the target masking was greatly reduced. In contrast, when the target and mask were perceived as moving or pulsating together, large masking effects were still produced. Thus increasing the observable separation between the target and mask as separate objects seems to drastically reduce OSM. This fact seems to show clear support of the OUT interpretation of OSM.

1.4.4 Summary

OSM is a recently discovered form of masking. In OSM, a target can be rendered imperceptible by four surrounding dots that act as a mask. That is, when the target and 4DM onset together and offset together, little masking is expected to occur. However, when the 4DM trails the target offset, perceptibility of the target is markedly reduced (e.g. Breitmeyer, 2014; Di Lollo et al., 2000; Lleras & Moore, 2003). OSM has been argued to be fundamentally different from other forms of masking in a number of key ways. The most critical of those is that re-entrant processing is argued to be a basic requirement for OSM to occur whereas other forms of masking are thought to occur earlier in the processing stream (Di Lollo et al., 2000).

There are currently two main theories of OSM, both of which explicitly or implicitly accept the role of re-entrant processing in OSM. The OSTM is the seminal theory of OSM. The central assumptions of the OSTM are based around the proposals that visual perception requires re-entrant activity (Di Lollo et al., 2000). OSM within this theory occurs as the consequence of the slowed processing that occurs within this re-entrant framework. The sluggishness of the re-entrant system is compounded when attention cannot be drawn to the target location (Di Lollo et al., 2000). In this instance, the percept of the mask alone is expected to replace that of the target and mask causing strong OSM according to the OSTM. Evidence of OSM with large set size displays and attenuation of it with spatial precuing has supported this claim (Di Lollo et al., 2000).

An alternate theory to the OSTM is provided by the OUT. Although the OUT assumes that re-entrant processing underpins OSM, it differs from the OSTM in terms of how masking occurs in relation to the target and mask representations. The OUT assumes that OSM occurs as the consequence of the target being represented by the same object-token as the mask as opposed to separate objects as in the OSTM (Lleras & Moore, 2003; Moore & Lleras, 2005). As such, OSM occurs as a consequence of the object-token representation of the target and mask updating to represent the mask alone when the mask trails the target offset. That is, when the target and mask are associated with one object-token representation, strong OSM is expected. In contrast, under conditions that favour a perceptual interpretation in which target and mask are encoded as separate perceptual objects OSM is found to be greatly diminished. As with the OSTM, the OUT assumes that attention is key to OSM occurring: attention must be disperse during the target presentation while also being focused on the mask during the trailing mask presentation. Support for the OUT has been found with manipulations of the relative target and mask locations and through apparent motion.

1.5 Feedforward theories of OSM

As stated in section 1.4 both the OSTM and OUT are fundamentally re-entrant theories as they assume that masking arises as a consequence of re-entrant processes. It is worth noting however that while the OUT assumes re-entrant processing this processing is not central to the theory, at least when compared to the OSTM.

Questions have been raised within the literature by a number of researchers and theoreticians as to whether OSM really constitutes an entirely new form of masking (as Di Lollo et al., 2000 claim), and whether it indeed requires a new theoretical framework to understand it. It has therefore been proposed by several authors that perhaps OSM could be explained by purely feed-forward models, in the same way as has been proposed for classical forms of masking (e.g. pattern masking, metacontrast).

1.5.1 Explaining OSM within a feedforward framework

Francis and Hermens (2002) argued that existing feedforward models of masking could be used to effectively explain OSM. Francis and Hermens modelled OSM using a number of mathematical models. It was found that three out of four feedforward models of masking could account for the OSM data on which Di Lollo and colleagues' (2000) OSTM was based (Anbar & Anbar, 1982; Bridgeman, 1971; Francis, 1997; Weisstein, 1968, 1972). The models Francis and Hermens evaluated were existing models of backward masking. Therefore none of these models make specific claims about the sparseness of contour of the mask nor do they posit any role for spatial attention. Francis & Hermens demonstrated that with minor modifications to the parameters of these models, these entirely feedforward models could fully predict the characteristics of OSM, at least in terms of the set size×mask duration interaction on which Di Lollo et al largely based the OSTM model.

These feedforward models have key characteristics in common with each other and also, to some extent, with the OSTM. Firstly, they all propose that the presentation of the target generates a trace representation of some form within the visual system; the strength of the target percept is based upon the magnitude of this trace. Secondly, all the models claim that the mask interferes or interacts with this target trace in some way. This causes the target trace to become smaller and reduces the strength of the target percept which ultimately results in target imperceptibility in most cases. It was argued from these findings that the interaction between the target and mask, rather than re-entrant processing, is integral to OSM.

Francis & Cho (2007) further investigated the value of feedforward model simulations in fitting OSM masking functions. They found that the model that fitted the OSM data best was based on mask-blocking (i.e. the target inhibits the effects of the mask at an SOA of 0), with an additional attentional element included. It was suggested that the sparse 4DM produces strong masking by generating some type of inhibitory response within the visual system. This inhibition increases with time meaning the prolonged mask duration leads to increased inhibition of the target trace. Within this model, attention is assumed to modulate the inhibitory effect of the mask. The inhibitory effect of the mask is small when attention can be focused upon the target and increases dramatically with increased spatial distribution of attention. This model matched the effectiveness of the OSTM when simulated for a surround mask.

Notably however, when the standard 4DM was simulated the model failed to effectively model OSM's core characteristics in terms of the data Di Lollo et al (2000) presented, particularly when compared with the predictions of the OSTM. This model predicted that the spread of attention would act to increase the masking effect (providing a weaker target signal) as is predicted by the OSTM. However, it was also noted that this model predicted OSM would produce a typical Type B, U-shaped masking function based on the hypothesised effects of mask-blocking. Furthermore, within this model the 4DM was predicted to produce a relatively weak effect due to its minimal contour. Modelling of the data however revealed a substantial monotonic decline in performance with increased mask duration, as predicted by the OSTM.

These modelling results taken together provide conflicting views on the effectiveness of feed forward only models in explaining the character of OSM, or at least the character of OSM as described by Di Lollo and colleagues (2000). However, overall these model simulations seem to suggest that OSM cannot be explained sufficiently by purely feedforward explanations of masking. Di Lollo, Enns & Rensink (2002) were particularly critical of this feedforward modelling approach to their OSM data. They argued that the claims that re-entrant processing is unnecessary for OSM is based on inappropriate modelling. Specifically this related to the way in which attention was modelled for this phenomenon and that key aspects of the Di Lollo et al (2000) findings were ignored (e.g. evidence for the dissociation between early inhibitory and late attentional effects in OSM).

1.5.2 Põder's attentional gating model of Object Substitution

Põder (2013) recently critiqued the OSTM. He argued that the OSTM is better thought of as a feedforward model than one of re-entrant processing as claimed by Di Lollo and colleagues (2000). Though Di Lollo et al presented the OSTM in terms of re-entrant processes; in actual fact the formal presentation of the model was essentially one which can be thought of in purely feedforward terms - i.e. without the requirement for re-entrant processing - according to Põder. It was therefore suggested that re-entrant processing may not be a necessary component in OSM if it is accepted that the OSTM can be understood as an *attentional gating model*.

Attentional gating models have relatively few assumptions. Such models have been shown to explain several visual phenomena including the attentional blink (Visser, Bischof & Di Lollo, 1999), attention, memory and decision making (Reeves & Sperling, 1986; Smith & Ratcliff, 2009; Sperling & Weichselgartner, 1995). Attentional gating has two main aspects: the first is that a stimulus generates a signal, the second it that this generated stimulus signal must be attended to. These two factors must be met to achieve a conscious perception of something (Põder, 2013; Sperling & Weichselgartner, 1995).

As such Põder (2013) proposed an attentional gating model of OSM based on the OSTM to examine this. This model included an unselective processing stage that incorporated divided attention. This unselective processing takes place prior to those mechanisms expressed in the OSTM. The OSTM is, in these terms, a single stage model. Accordingly, the OSTM implicitly assumes that processing only starts when an object is subject to attention. That is, no preattentive processing is posited to occur (beyond that required to guide attention to the target location). During this stage, attention is able to span the whole stimulus display and retrieve information relating to the target. As with the OSTM, the supposed role of set size (i.e. the set size×mask duration interaction) that appears evident from Di Lollo et al's (2000) original data is accounted for by Põder's (2013) model. That is, this model predicts that the amount of information relating to the target that is attended to is dependent on set size. Within this model, the larger the set size, the poorer the signal-to-noise ratio will be.

This model assumes that under masking conditions the sensory response relating to the mask continues to grow while that of the target does not (when the mask trails the target offset). In these instances, the sensory response of the mask continues to grow after target offset while simultaneously adding noise (i.e. suppressing) to the decaying sensory response relating to the target. This means that the target representation is likely to be suppressed causing impaired target visibility. In contrast, when the target and mask both offset together, the likelihood of the signals for both stimuli being preserved at the object perception level is high. Põder (2013) therefore assumed that attention is a factor in OSM, however the assumption is perhaps less central to the workings of the model than it is to the OSTM. Rather, attention is argued to modulate the strength of and extent to which temporal integration between the target and mask signals occurs. Põder found that this model provided a good fit to the original OSM data (Di Lollo et al., 2000).

Põder (2013) argued that the addition of a pre-attentive processing stage to the OSTM would potentially help resolve some of the theoretical inconsistencies which Põder highlights in the OSTM; this is particularly the case concerning the issue of re-entrant processing. As such, the two stage model that Põder proposed could be easily adapted for use with the OSTM and importantly does not require re-entrant processing. In this revised model the unselective processing stage initially divides spatial attention across the whole visual display. When the mask then trails the targets offset the stronger mask signal leads to target processing being interrupted.

Põder's (2013) attentional gating model has been criticised by Di Lollo (2014) however. In particular Di Lollo argued that the proposal that the trailing mask produces noise proportional with mask duration – a key assumption of the attentional gating model – lacks any empirical support in the literature (*c.f.* Põder, 2014). Given this fact Põder's model, though a plausible alternative to the OSTM and thus potentially a more parsimonious model, currently lacks any empirical support. Furthermore, it makes no obvious testable predictions which would distinguish it from the OSTM. There are also empirical reasons for rejecting the attentional gating model. For example, the model has some difficulty explaining some of the electrophysiological evidence indicating re-entrant processing in OSM including N2pc activation for masked targets (Woodman & Luck, 2003) and intact feedforward processing in OSM with affected re-entrant processing (Harris, Ku & Woldorff, 2013; Reiss & Hoffman, 2007).

1.5.3 Summary

Some researchers have argued that the claim regarding the involvement of re-entrant processing in OSM lacks parsimony as an explanation. It may be an overly complicated account of the actual underlying processes. A number of researchers have tried to show that, perhaps, OSM can be explained by simple feedforward models, i.e. ones of the same class that have been proposed for other types of backward masking. These models have generally proposed that OSM occurs through inhibitory interactions between the mask and target signal (e.g. by causing an inhibitory response to the target percept; by the presence of the mask increasing target signal-to-noise) resulting in weakened target strength (Francis & Cho, 2007; Francis & Hermens, 2002; Põder, 2013).

These feedforward models have the advantage of being more parsimonious in their assumptions and not requiring the assumption of re-entrant processing. However, these models have come under question for a number of reasons. The models simulated by Francis and Cho (2007) and Francis and Hermens (2002) largely failed to account for the effectiveness of such a sparse mask to prevent perceptibility of the target. The attentional gating model proposed by Põder (2013) has also come under criticism from Di Lollo (2014). The predictions made by this model are currently lacking empirical support in the same way that was claimed of the OSTM. It still remains to be seen how useful feedforward models are in understanding and explaining the multifarious sources of evidence regarding the characteristics of OSM. As such, in their current instantiation feedforward models do not seem to be the answer to OSM's theoretical issues and they make few if any uniquely testable predictions which allow them to be empirically distinguished from the OSTM. Moreover, given the clear evidence to suggest that the visual system has a re-entrant organisation, it could be argued that re-entrant processing should be a starting point for any theory of masking (Di Lollo et al., 2002).

1.6 The role of attention in OSM

As has been discussed in section 1.4, the OSTM assumes a vital role for attention in OSM. This attentional component has been explored in various ways. These include stimulus "pop out" (i.e. the perceptual distinctiveness of a stimulus in a display), display set size (i.e. the number of display items presented with the target) and spatial cuing methods (in which attention is directed either exogenously [externally] or endogenously [internally] to or away from the target location). However, recent evidence has questioned the proposed role of attention in OSM and has argued that, at the very least, the claims regarding the role of attention in the phenomenon have been radically overstated. This research will be discussed towards the end of this section.

1.6.1 The role of set size in OSM

To recall, the role of distractor number (i.e. set size) is, according to the OSTM instrumental in determining whether OSM occurs and the extent to which it occurs (see section 1.4.2). In the original OSTM set size (i.e. the number of items [target+distractors] present in the stimulus array) was argued to be a fundamental variable dictating the occurrence of OSM. When the target was alone in the stimulus array (set size =1) OSM was reported to not occur; as set size increased (by adding distractors) the masking effect (as indexed by the effect of mask duration) was reported to increase monotonically. Within the OSTM OSM was argued to show a multiplicative relationship with set size because set size was viewed as a proxy for attention. As set size was increased so was the spread of spatial attention (Di Lollo et al., 2000). This involvement of set size will be further explored in this section.

Di Lollo and colleagues (2000) conducted a number of experiments which seemed to strongly support the proposed role of set size in OSM. They found that regardless of the type of mask used, an interaction consistently occurred between set size and mask duration. These experiments showed, as predicted, that set size affected OSM. With a set size of 1, there was a minimal decline in performance with increased mask duration. Equally, when the target and mask offset in synchrony there was a minimal reduction in performance regardless of set size. However, as set size increased, the masking effect became more apparent, particularly with a mask duration extended beyond ~40-80ms; with maximum effectiveness at a set size of 16. Thus the lowest overall performance in their data tended to be with a set size of 16 and a mask duration of 320ms. This interaction was also found across task (identification and detection) and stimulus type. This shows a clear interdependency between set size and mask duration in the OSM paradigm. These results thus provided strong support to the OSTM's claim that OSM is dependent on set size effects.

Despite the seeming importance of set size in OSM, there are surprisingly few empirical investigations of it as a variable. Instead, the majority of research, assuming the original claims of Di Lollo and colleagues (2000) to be correct, has tended to keep set size fixed. The small number of studies that have manipulated set size are evaluated here.

Jiang & Chun (2001) reported an effect of set size in OSM in a between subjects comparison of two of their experiments that used different set sizes. Participants were asked to identify a target letter in a set size of one or eight. The results showed a significant interaction between set size and mask duration, indicating that OSM magnitude increased as set size increased. Enns (2004) in one partial report study also found an effect of set size with OSM in which the display set size was varied between one and seven letters. The offset of the mask was varied between 0 and 600ms post target. It was found that with a set size of one, performance was relatively unimpaired regardless of the length of the trailing mask. However with a set size of seven, there were substantial performance impairments with a 150ms mask interval onwards.

More recently Kotsoni, Csibra, Mareschal and Johnson (2007) and Goodhew et al (2012) reported further empirical support for the presence of a set size effect in OSM. Kotsoni and colleagues used a target detection task with two set sizes (1, 9). Participants were required to identify whether a vertical line bisected the target circle (identifiable by the surrounding 4DM). Across two experiments they found that OSM was strongest as a combined function of larger set size and trailing mask duration. That is, the trailing mask had little effect at a set size of 1 while having a substantial effect with a set size of 9.

Goodhew et al (2012) again examined the effect of set size on masking magnitude. Participants were required to identify the orientation of a target Landolt C (left, right) that was identifiable by the surrounding 4DM. The target was either presented in isolation or with eight other Landolt C's (set size 1, 9 respectively). They found set size increased masking magnitude in two studies. However, they failed to find a set size effect in one experiment. It was argued that this failure was because strong masking occurred across all mask durations with a set size of 9 (including 0ms).

Summary

The evidence presented in this section provides clear support for the claim of the OSTM that increased display set size is an important element of OSM. That is, these findings have shown that little masking by OSM is created when the target is the sole item in the display. However, when the number of display items is increased, substantial masking is seen when the 4DM trails the target offset. These findings therefore suggest, as is claimed by Di Lollo and colleagues (2000) that the distribution of spatial attention in essential for OSM to occur.

1.6.2 The effect of "pop out" in OSM

"Pop out" refers to the ability of a single display item to be easily detected within a large stimulus array. It is typically demonstrated in the context of a visual search task. The "pop out" effect occurs when the item is distinctive from the other display items on a given feature for example a red circle within an array of black circles, under such conditions a "pop out" target can be rapidly located within a display (Treisman & Gelade, 1980; Wang, Cavanagh & Green, 1994).

As mentioned in section 1.4.2., during Di Lollo and colleagues' (2000) initial investigation into OSM the effect of "pop out" was examined. They found that when the target item "popped out" of the display due to it possessing a unique feature (the target was an annulus with an intersecting vertical bar; all other items consisted of an annulus without a bar) masking was effectively abolished (as measured by the ability to determine the presence/absence of the vertical bar on the target). Di Lollo and colleagues interpreted this effect as being attentional in nature. It was argued that the "pop out" of the feature caused attention to be more rapidly drawn to the target location, thus reducing OSM. Since this initial investigation of "pop out" in OSM, numerous other researchers have replicated the "pop out" effect and aimed to further understand the underlying nature of its operation. These studies will be explored in this section.

Moore and Lleras (2005) examined "pop out" in OSM by independently manipulating the target and mask colours. This colour manipulation had a substantial effect on OSM in that strong masking was only produced when the target and mask were the same colour. Masking was greatly reduced when the target and mask appeared in distinctly different colours (e.g. red target, green mask). This colour separation potentially caused increased distinctiveness or "pop out" of the target that assisted in separating the target and mask representations.

Gellatly, Pilling, Cole and Skarratt (2006) continued this investigation of "pop out" in OSM. Gellatly and colleagues however examined dimensionally specific effects of "pop out" in OSM. In these experiments "pop out" could occur either for the colour or orientation dimension. The required response was equally likely to relate to the "pop out" that had occurred or not (e.g. "pop out" could occur for orientation with a colour identification task [unrelated] or an orientation identification task [related]). It was found that reduced masking was found only when the "pop out" occurred on the dimension for which the report needed to be made; where the "pop out" was on a different dimension no benefit was seen on masking. For instance if a target popped out from the mask in terms of its orientation, there was little masking found when observers were asked to report the orientation of the bar. Gellatly et al (2006) did not explain their results specifically in terms of attentional capture by the "pop out" item. Rather they suggested that the results indicated that OSM is a phenomenon which occurs prior to the binding of the target features into a coherent percept, a claim also made by Bouvier and Treisman (2010) based on similar evidence.

Tata and Giaschi (2004) looked at the role of “pop out” in OSM from a slightly different perspective. They instead investigated how the pop out of the mask was important in producing OSM. In traditional OSM paradigms the 4DM is unique in the display. Furthermore the traditional OSM paradigm is argued to require explicit attention to the mask object. Typically the 4DM is used to identify the target item within the array as well as performing as a trailing mask. They argued that this fact may, in part, explain OSM effects. Additionally, in standard OSM paradigms, after the offset of the stimulus array the trailing mask is typically also a singleton item in the display. It is known that the presence of singleton items tends to involuntarily capture attention in a bottom-up manner (e.g. Theeuwes, 2004). Thus the stimulus displays in OSM (singleton mask) could lead to rapid attentional selection of the mask which in fact causes OSM, perhaps by drawing attentional resources *away* from the target.

To test this, a modified OSM paradigm was presented in which mask (rather than target) set size was manipulated. That is, in one condition (mask set size 1) a single mask was present at the target location (as is standard in OSM paradigms), in another condition (mask set size 8) square masks were presented around all eight stimulus array locations. Participants were required to identify the presence of an “O” presented within an array of “C”s. This meant that the target and mask of interest were embedded within the distractor display. For single mask trials, performance showed a typical monotonic decline in performance as mask duration increased. However, with a mask set size of eight there was little effect of mask duration; in other words the OSM effect was largely abolished.

These findings suggest an additional role of attention in OSM to those specified by Di Lollo and colleagues (2000). Just as the work of Di Lollo et al suggested the importance of attention towards the target in determining the occurrence of the OSM effect, Tata and Giaschi's (2004) findings suggest that attention to the mask is also critical for the effect. This seems to indicate that the object substitution process relies on attentional selection of the mask itself, an issue also postulated by the OUT (Lleras & Moore, 2003). Under standard OSM conditions attention may tend to be drawn away from the target towards the ("pop out") mask, reducing target processing and thus leading to masking, the extent of the capture being determined by the duration of the mask.

Summary

The evidence presented in this section seems to indicate the importance of object level representations in OSM. Where the target and mask seem to be encoded as a single representation by the visual system then OSM is most evident. In contrast, when the experimental conditions favour the target being represented as separate from the mask, OSM is largely attenuated. As such, this would suggest that OSM occurs at least in part at the level of competition between object token representations as postulated by the OUT.

1.6.3 Spatial cuing, attention and OSM

As part of their initial investigation of OSM, Di Lollo and colleagues (2000) explored spatial precuing as a way of examining the role of attention in OSM. This research seemed to indicate that the use of a spatial precue to draw attention to the target location prior to its onset greatly attenuated OSM. Since this initial investigation, numerous researchers have used spatial precuing as a way of garnering information about the role of attention in OSM.

Jiang & Chun (2001) found a seeming effect of spatial precuing on attention. In their experiment the 4DM was presented either surrounding or to one side of the target (more central or peripheral) and either a neutral or valid cue was used. Valid precuing led to a reduction in masking, regardless of the mask duration while the neutral cue had no effect. Additionally, performance was most improved by the spatial precue when the mask did not surround the target. This suggests that attention towards the target can more effectively diminish the updating effects of the mask when they are more clearly represented as separate objects.

Enns (2004) again used a spatial cuing paradigm to investigate the role of attention in OSM. In a series of experiments, Enns replicated the result that masking is reduced when attention can be rapidly drawn to the target location. As with Jiang & Chun (2001), the presentation of a precue prior to target onset (a small dot adjacent to the target location) was found to substantially diminish OSM. Moreover, the length of time the precue was displayed for made little comparative difference to performance. This seems to suggest that once attention has been drawn to the target, extended viewing of it does not have any additional beneficial effect.

Luiga and Bachmann (2007) examined the role of endogenous (i.e. top down) and exogenous (involuntary) spatial precues on OSM. They conducted two experiments in which a central (endogenous), location specific (exogenous) or no cue was presented prior to the stimulus array. The cue in each instance was a 4DM. It was found that when attention was automatically drawn towards the target location with the exogenous cue, OSM was attenuated. However, strong OSM persisted both when no cue was presented and with an endogenous cue. This again seems to suggest a role for attention in OSM. It also suggests that this role was limited to situations in which attentional guidance was stimulus driven. Where the direction of attention was voluntary in nature no effect was produced on OSM.

Germeys, Pomianowska, De Graef, Zaenen and Verfaillie (2010) continued the examination of exogenous and endogenous spatial cuing in OSM. As with Luiga and Bachmann (2007), Germeys and colleagues used a location specific exogenous cue and a central arrow endogenous cue. They found, as with Luiga and Bachmann, that exogenous spatial precuing attenuated OSM. However unlike Luiga and Bachmann, they also found that endogenous precuing substantially reduced OSM. These differences in results between Germeys and colleagues and Luiga and Bachmann were explained by experimental design differences, particularly in terms of the way in which endogenous precuing was manipulated. This result seemingly suggests that any method of precuing that enables attention to be drawn towards the target location more rapidly can substantially reduce OSM.

Furthermore Koivisto (2012) also reported that masking of the target significantly decreased target detection while precuing of the target location attenuated masking. When examining subjective confidence intervals, participants seemed to be less confident for trials in which the target was missed than in those where a correct rejection was made. This was interpreted as suggesting that participants were able to initially attend to the target under masked conditions and that the initial feedforward processing of the target, at least, remained intact.

Summary

Findings from many cuing studies have given support to Di Lollo et al’s (2000) claim that OSM is strongly modulated by attention. When attention is dispersed across the display, strong OSM is observed; in contrast, when attention is able to be quickly drawn towards the target location (by use of spatial precuing) OSM seems to be greatly attenuated.

1.6.4 Is spatial attention actually important in OSM?

The evidence presented in section 1.6 up to this point has indicated that OSM is strongly modulated by attention. However, more recent results provide compelling evidence against the proposed fundamental role of attention, showing that seeming attentional variables, while affecting overall perceptibility in fact have no effect on OSM itself. Instead these recent studies have argued that the initial reports of attentional effects, particularly in regards to the role of set size, are actually related to constrained performance.

One of these attentional variables that has come under question is that of set size. Specifically, questions have been raised over whether the presence of distractors (and the presumed diffusion of attention which results) is a necessary condition for OSM to occur. These findings have suggested that the “interactions” reported previously may be spurious and unreflective of the true character of OSM. It is argued that they may be no more than an artifact of restrictions in the measurable range of performance within these experiments. Argyropoulos, Gellatly, Pilling and Carter (2013), in a series of experiments closely modelled on those of Di Lollo et al (2000), repeatedly failed to produce a significant interaction between set size and mask duration (see Figure 3, plate A). These findings were seemingly in direct contradiction with Di Lollo and colleagues’ original claims. Importantly, masking (as indexed by mask duration) was just as strong with one display item as it was with twelve items. Argyropoulos et al argued that the set size interaction reported by Di Lollo et al (and by others in section 1.6.1) was, in most cases, the consequence of ceiling effects in measureable performance. That is, performance was at or close to 100% correct for all levels of mask duration where set size was small (i.e. for set sizes 1 and 2 in particular) in all these experiments.

Argyropoulos and colleagues’ (2013) finding is not an isolated one. More recent research by Filmer, Mattingley and Dux (2014), inspired by Argyropoulos et al’s findings also looked at the effect of set size on masking using an eight alternative forced choice task. The observer was required to report the orientation of a bar superimposed on the circumference of a target circle (identifiable by the surrounding 4DM). Filmer and colleagues varied the set size of their display between 1 and 16 items (1, 8, and 16). They again failed to produce an interaction between set size and mask duration in OSM when ceiling effects were accounted for (see Figure 3, plate B). The only time a significant interaction between set size and mask duration was produced, it was revealed to be the result of ceiling effects at set size 1. These findings provide additional evidence to support the claim that set size is not an important variable in OSM.

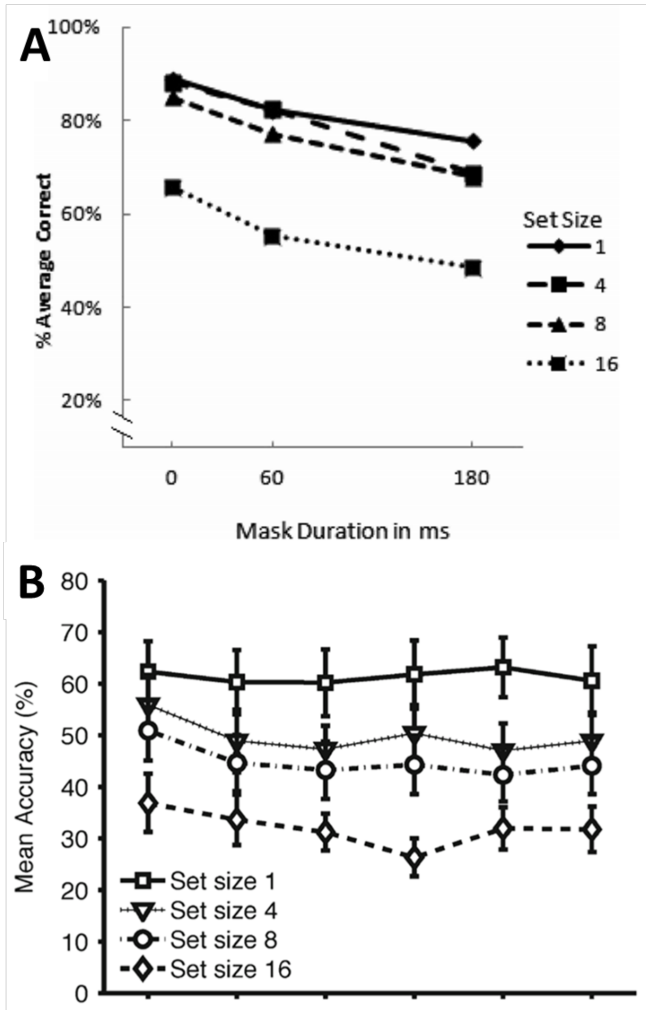

Figure 3| Performance in Experiment 3 of Argyropoulos et al (2013; Figure 6, page 15) and Experiment 2 of Filmer et al (2014; Figure 3, page 6) in plates A and B respectively. Mask durations were 0, 80, 160, 320 and 400ms in Filmer et al (2014). Mask durations were 0, 60 and 180ms in Argyropoulos et al (2013).

Further evidence in this vein has also been shown in respect to cuing in OSM. In all cases in which a cuing effect was reported in OSM (see section 1.6.3) there are issues with the data which make interpretation of the effect somewhat perilous. In many of the studies ceiling effects were clearly evident, particularly in the cued conditions making it hard to determine the effect of the mask (or the results were open to alternative explanations; see Argyropoulos et al., 2013; Pilling, Gellatly, Argyropoulos & Skarratt, 2014). This is the case with the evidence presented by Di Lollo and colleagues (2000) for the beneficial effects of precuing as just one mask duration was used. Thus these findings can only show that precuing is effective at this one mask duration.

Pilling and colleagues (2014) again examined precuing in OSM. In one experiment their investigation was centred on the impact of valid and invalid spatial cues. In these experiments a comparison was made between valid and invalid cues, or for cues that were always valid but varied in their asynchrony with the target. When the asynchrony was varied the cue in some trials temporally led the stimulus array. In line with previous results, valid precuing of the target location improved performance (this was particularly evident when a 150ms valid pre-cue was compared with a 0ms valid pre-cue) whereas prolonged mask duration decreased performance. Critically though, in contrast to previous results, precuing did not have an effect on OSM specifically. That is masking was no stronger when attention was drawn away from the target by an invalid precue. Thus, the same explanation of attentional effects in OSM relating to constrained performance appears to be true for cuing as well as for set size.

Furthermore, these results were found even when all potential targets were masked. In contrast to Tata & Giaschi (2004) therefore, masking was produced even when masks were presented surrounding all possible targets (though it was found that the overall amount of masking was lower than when there was a single trailing mask). This means that

OSM was produced even when there was no potential for mask pop out. Importantly, invalid target precuing still did not lead to increased masking. In fact, the only time an interaction was produced between cuing and mask duration was when the heterogeneity of the distractors was manipulated. Cuing only had an effect on masking when the target was displayed with distractors of the same stimulus category that had high variability between them. Thus adding additional spatial uncertainty (noise) rather than a dispersal of attention per se potentially inflates masking. Consequently, these findings suggest that spatial attention is not the fundamental component of OSM as claimed by Di Lollo et al (2000).

Further evidence for the irrelevance of attention as a variable in OSM was recently presented by Filmer et al (2015). They used a paradigm that aimed to definitively resolve the extent of attentional involvement in OSM. A target only paradigm was used in which both exogenous and endogenous attention was always focused on the target. Strong masking was still able to be produced when the target was foveated and attended to. These results definitively show that OSM can be obtained when spatial attention is not spread, and is in fact fully attended towards the target location. As such, this is the most compelling research to date to suggest that the distribution of spatial attention is not a fundamental aspect of OSM.

Further research by Pilling (2013) however inadvertently provided support for the role of spatial attention in OSM with a set size manipulation. This experiment was exploring the effects of target and mask preview. Different display sizes were used in order to assess the consequences for preview effects. While the set size manipulation had relatively little influence on the preview effects it did seem to influence the overall amount of masking. Given the number of factors involved and because it was not the variable of primary interest, set size was only manipulated as a between participants factor. Nevertheless, these findings suggest that at least in certain instances set size can impact OSM when performance falls within a measurable range. Thus the findings presented by Pilling at least suggest that the complete dismissal of distractor effects as a factor in OSM may have been premature. As such, these findings indicate that perhaps the spread of attention is important in OSM under certain conditions.

Summary

Initial reports of OSM found the spread of attention to be a vital component in line with the OSTM. Namely, these investigations have included known attentional modulation effects such as “pop out” and spatial cuing. These features that draw attention towards the target (location) were found to markedly reduce OSM (Enns, 2004; Gellatly et al., 2006; Germeys et al., 2010; Jiang & Chun, 2001; Moore & Lleras, 2005). However, more recent research has suggested that this spread of spatial attention is perhaps not as important as initially claimed.

Recent research has found that while attentional modulation effects such as set size and “pop out” substantially affect overall perceptibility of the target (decreasing and increasing respectively), they have little influence over OSM (Argyropoulos et al., 2013; Filmer et al., 2014; Pilling et al., 2014). Even more compelling evidence to suggest that the spread of attention is not important for OSM was presented by Filmer et al (2015). They were able to produce strong OSM for a single, foveated target. These most recent findings suggest therefore that at the very least, spatial attention is certainly inessential for OSM to occur. The effect on OSM seems to be modest at best, indeed if there is any effect at all. Further research by Pilling (2013) however indicated that the role of attention, as expressed by set size, may have been prematurely disregarded. This research indicated that set size, and thus attention, can increase the magnitude of OSM, at least in certain instances.

1.7 Aims of the thesis

The findings presented by Argyropoulos et al (2013) and Filmer and colleagues (2014) suggest that set size at the very least, is not the hallmark of OSM as was originally claimed in Di Lollo and colleagues' (2000) original description of the phenomenon, and in the OSTM, the formal model of OSM that they proposed (Di Lollo et al, 2000). However, the claim that these set size effects on masking are entirely a consequence of constrained performance may be a premature one (Pilling, 2013).

With this in mind, it is clear that set size cannot be ruled out as a possible factor in OSM, at least under some circumstances. Therefore the results of Pilling (2013) are used as the starting point for this thesis to further investigate if the role of set size should be taken into account. Understanding the role of set size is important firstly, for methodological reasons in terms of future study design in OSM and secondly, given the theoretical significance attached to set size as a variable in the original description of OSM. As was noted earlier, set size tends to be viewed as a proxy for the spread of spatial attention – the role of set size can therefore be taken as a measure of the extent to which the OSM effect is attention-dependent. If set size has no influence on OSM then this seems to rule out or at least cast serious doubts over the possibility that OSM has anything to do with spatial attention.

The aim of this thesis is therefore to investigate the character of OSM in relation to the role of high level processes, namely whether there is a selective attentional component in OSM. The first aim of this thesis is to clarify the role of set size in OSM, to determine whether, as Pilling (2013) showed, set size does indeed influence OSM when performance is within a measurable range.

The central tenant of the current understanding of OSM is that it depends on high level processing to occur which has not been found to be relevant in other forms of masking (Di Lollo et al., 2000). Di Lollo and colleagues (2000) argued, in the OSTM, that the spread of attention, operationalised as the display set size was vital for OSM to occur and determine the magnitude of the OSM effect. Given the importance that the set size variable was given in the OSTM it seems more than reasonable to investigate if indeed there is an effect on OSM and to empirically determine the circumstances in which it occurs.

1.8 Outline of the thesis

- *Chapter 2 – The role of set size in object substitution masking*

  This chapter explores the relationship between set size and OSM. This is done in numerous ways across 5 experiments, in terms of varying the types of stimuli, the number of response options, and the type of task. The aim of this chapter is to examine if set size as a variable plays any role at all in OSM. Principally this set size effect will be investigated by exploring if there is an interaction between set size and mask duration. The central finding of this chapter is that set size does in fact appear to influence OSM across a varied range of stimulus and task conditions under circumstances where ceiling and floor effects are not evident.

- *Chapter 3 – The role of crowding in object substitution masking*

  Chapter 2 established that varying set size influenced OSM; the larger the set size the more masking was obtained. This chapter explores the basis of this set size effect. It is expected that the effect of set size could in fact be a consequence of crowding, rather than set size itself. Crowding refers to the deleterious effect of nearby stimuli to a target stimulus. The extent of crowding is increased with reduced spatial proximity between a target and other stimuli. As increasing the display set size leads to a reduction in the spatial proximity between each of the stimuli, crowding presents a natural confound. It could therefore pose an alternative explanation to set size of what causes masking magnitude to increase in OSM.

This chapter will begin by introducing the phenomenon of crowding and reviewing the literature on this topic. The effect of crowding in OSM will then be experimentally investigated. This will initially involve decoupling crowding from set size in an experimental paradigm. The factors of crowding and set size will be varied independently from one another in the same experiment. To pre-empt the results of this experiment, it was found that only crowding affects OSM while set size affects overall performance but not OSM itself. Once it was established that crowding is the important variable in OSM, crowding was manipulated in a more systematic way. This was done by systematically varying the distance between the target and distractors in the aim of determining the window of the crowding effect in relation to OSM. It was found that in contrast to standard crowding, the effect of the interaction between OSM and crowding was most prominent at medium distances: the magnitude of OSM was greatest at a medium distance between the target and flanking distractors, not at the closest given distance which was predicted to be the case.

Interestingly these findings show clear parallels with a recently reported phenomenon from the crowding literature described as "supercrowding" (Vickery, Shim, Chakravarthi, Jiang & Luedeman, 2009). Here it has been shown that masking a target with a weak, low level mask can increase the window of crowding. Given this, it seemed plausible that the interaction between crowding and OSM presented in Chapter 3 was not an effect of crowding on OSM, but actually an effect of *OSM on crowding.* That is, the effect of OSM on the target was to increase the range in which crowding of the target occurred. This is in contrast to the expectation that the interaction between crowding and OSM related to an effect of crowding on OSM which increased the magnitude of OSM.

- *Chapter 4 – An investigation into the electrophysiological correlates of OSM and crowding*

  This chapter explores the electrophysiological underpinnings of OSM and the interaction between crowding and OSM. The aim of this research is to understand the neural underpinnings of the potential influence of OSM on crowding. Specifically, this research will attempt to better understand the time course of this process. The ERP correlates *P1* and *N1* will be used in the aim of empirically examining this. The behavioural paradigm was able to replicate the inverted U-shaped interaction between crowding and OSM. However, the results of this chapter revealed no significant effect of the interaction between crowding and OSM on early visual ERP amplitude. Thus, the results of this study suggest that perhaps the effect of OSM on crowding does not occur during the early stages of visual object processing, or if it does it has no obvious electrophysiological correlate. Equally however, it may be that the paradigm used in Experiment 11 was not sensitive to these neural correlates. As such, early visual processing effects cannot be unequivocally dismissed.

- *Chapter 5 – Discussion of results*

  This chapter will start by summarising the aims and findings of this thesis. It will then attempt to bring together the findings from the previous chapters to provide a meaningful evaluation of the role of set size, crowding and spatial attention in OSM. These findings will be discussed in terms of the existing literature and theories of OSM (and crowding) as well as their implications. Future research directions will be raised and conclusions will be drawn from the thesis in its entirety.

Chapter 2| The role of set size in object substitution masking

2.1 Introduction

As discussed in Chapter 1, the assumption that the presence of distractors is necessary for OSM to occur (Di Lollo et al., 2000) has been questioned by several recent experimental findings. Recent research (Argyropoulos et al., 2013; Filmer et al., 2014) has indicated that at the very least, the presence of distractors is inessential for producing OSM, contrary to what was originally claimed by the OSTM (Di Lollo et al, 2000). However, what is still unclear is whether the findings of Argyropoulos et al (2013) and Filmer et al (2014) are definitive in their ruling out of any role of distractors in OSM. It is notable that both studies used similar tasks to assess masking, both mostly involved discrimination tasks in which observers either had to report the position of a gap or line on a Landolt circle or square. These were the same types of tasks as used by Di Lollo and colleagues (2000) in their initial reporting on OSM.

The current experiments presented in this chapter aimed to look at set size effects using a different stimulus class, that being digits. This was done to test whether the reported independence of set size and mask duration in OSM (Argyropoulos et al, 2013; Filmer et al, 2014) also holds where the stimulus array is composed of such stimuli. Digit identification – in requiring processing of conjunctions of features – is likely to involve more complicated perceptual processing of the stimulus than discrimination of a single feature such as a gap position. As a consequence where the stimulus array is composed of digits and the task requires identification, distractor effects may be more apparent than was the case with the simple Landolt discrimination tasks used in Argyropoulos et al (2013) and Filmer et al (2014).

Digit (and letter) identification tasks have frequently been used to investigate the OSM paradigm. This can be seen in a number of papers including Jiang & Chun (2001), Enns (2004), and most recently in Pilling et al (2014). For this reason, given the reported findings of Argyropoulos et al (2013) and Filmer et al (2014) it seems provident to determine if their findings extend to situations in which other classes of stimuli such as digits are used.

This question becomes more pertinent in light of the recently reported findings by Pilling (2013) which used digits as stimuli and found group differences in set size effects. The main objective of this particular study was not to look at the set size×mask duration interaction per se, rather it was to explore and compare the character of the target and mask preview effect in OSM. The study found little evidence of any effect of set size on preview effects. However it did show an overall effect of set size on masking itself. The results of Pilling seem to indicate that set size, at least in certain instances, can influence OSM. Perhaps this stimulus class is more sensitive to OSM than the more basic (Landolt) stimulus types used by Argyropoulos and colleagues (2013) and Filmer and colleagues (2014) for example. However the aim of the Pilling study was not specifically to explore the set size variable in relation to masking. Set size was constant for any participant in this study. The effect of set size on masking could only be ascertained through comparison across two separate participant groups in which the set size was four and eight respectively.

Nevertheless the findings do seem to be a counterexample to the claims of Argyropoulos et al (2013) and Filmer et al (2014) that set size and mask duration are independent in OSM and therefore the finding of Pilling (2013) warrants further exploration. This will be done by repeating the use of digits as stimuli while varying set size. However, set size will be varied as a within-participant variable with three levels of set size, rather than as a between-participant variable with just two levels.

Were the results to again demonstrate independence between set size and mask duration it would be further support for the claims of Argyropoulos et al (2013) and Filmer et al (2014) that distractors have no influence on OSM. Furthermore, given that set size is deemed to be a proxy variable for attention a failure again to find an interaction between set size and mask duration would constitute further evidence against the role of attention in OSM. Such findings would produce serious difficulties for the OSTM, as attention is an integral element of the theoretical account of OSM. For these reasons it seems reasonable to investigate the effect of set size in OSM in the context of digits. In this chapter five experiments were conducted to examine the interaction between set size and mask duration using digit identification and detection tasks and a Landolt discrimination task.

2.2 Experiment 1: Target identification task (10 alternative forced choice)

The purpose of Experiment 1 was to test the findings of Argyropoulos et al (2013) and Filmer et al (2014) in the context of a different task and with a different stimulus class. Its purpose was also to try to replicate the finding of Pilling (2013) where an interaction between set size and mask duration was observed in the data in contrast to the finding of Argyropoulos et al and Filmer et al that set size and mask duration were found to not interact.

As a method of investigating OSM, using a digit identification task conceivably holds an advantage over the Landolt discrimination task used by Di Lollo et al (2000) and Argyropoulos et al (2013). The digit identification task involves ten response options (0-9), making the baseline probability of correct random responding .1. This means that the likelihood of getting a correct response by chance is lower than in Argyropoulos et al, Di Lollo et al and Filmer et al (2014). This makes it easier to distinguish non-random from random responding in a participant under conditions where accuracy is expected to be low. Thus a digit identification task is well suited to the purpose of measuring target perceptibility and exploring the potential interactive effects of set size and mask duration.

Method

Participants

Seventeen first year Oxford Brookes Psychology students (14 female) took part in the experiment. All participants reported normal or corrected-to-normal visual acuity. This and all further experiments were approved by the Oxford Brookes University Research Ethics Committee (UREC registration No. 130698). All participants gave informed consent and received course credits or payment for taking part in the experiment. The number of participants used in the experiments within this thesis was based on the numbers used in previous literature of this type.

Design

The experiment had two within-subjects independent factors, each with three levels. These were *set size* (1, 6, or 12 items) and *trailing mask duration* (0, 60, or 180ms). It is the length of this trailing mask after the target offsets which is the relevant variable for masking in OSM. The dependent variable was *identification performance*, measured by the percentage of correct responses.

Stimuli and procedure

The experiment was conducted in a darkened and sound deadened room with back lighting. Stimuli were presented on a 20 inch flat screen Sony Trinitron CRT computer monitor set at a resolution of 1024×768 pixels running at a 100Hz refresh rate. The monitor was controlled by an Intel Pentium 4 (2.66 GHz) PC fitted with a NVDIA GeForce 4 graphics card. The monitor was viewed by the participant from a distance of approximately 110cm. Software written in the BlitzMax programming language (BlitzMax V.1.5; Sibly, 2011) controlled all aspects of stimulus presentation, randomisation and response recording.

All stimuli were black (0.03cd/m^2) presented on a white (97cd/m^2) background. The stimulus array consisted of 1, 6 or 12 digits depending on the set size condition. Digits were in Arial font Pt. 32 (0.47° subtended visual angle in height) and were centred on the circumference of a virtual circle (itself with a radius subtending 3.9° from the centre of fixation to the centre of each digit) with a fixation cross at its centre. Digits were evenly spaced apart from one another on the virtual circle (except in set size 1 arrays where only one digit is presented). Participants were required to identify the target digit (indicated by the surrounding mask). The mask consisted of four dots forming a virtual square (subtending 0.89° in width and height respectively) around the target. The dots comprising the mask were each 0.10° of visual angle in width and height respectively. The identity of the target digit was randomly determined on each trial with the constraint that each of the ten digits appeared with equal frequency within all trial types. Distractor digits were chosen randomly for each trial in which distractors were present.

Each trial began with a blank white screen presented for 500ms followed by the onset of the fixation cross which was accompanied by a brief alerting tone. After a further 250ms the stimulus array was presented with the four dot mask surrounding the target digit. The stimulus array remained on screen for 40ms and was followed by the trailing mask either for 0 (non-masked control condition), 60, or 180ms. The fixation cross was onscreen throughout these frames and remained until the participant responded. Responses were made on a standard computer keyboard, pressing a key from 0-9 corresponding to the target identity. Participants were given immediate aural error feedback following an incorrect response key press. On a key press the fixation cross disappeared and a new trial was instigated. A schematic depiction of the trial sequence is given in Figure 4.

There were 540 randomly ordered trials, 60 for each combination of mask duration and set size presented in 10 distinct blocks. The computer prompted the participant to have a brief break after every 54 trials. The experimental session was initiated by verbal instructions from the experimenter. Participants were informed that accuracy rather than speed of response was important for the experiment. Three randomly selected demonstration trials of the experiment with slowed display sequences were shown to the participant. The participant then completed 30 practice trials which were randomly selected and where the timings were the same as the actual experiment followed by the experimental trials. The duration of the entire experimental session was approximately 30 minutes.

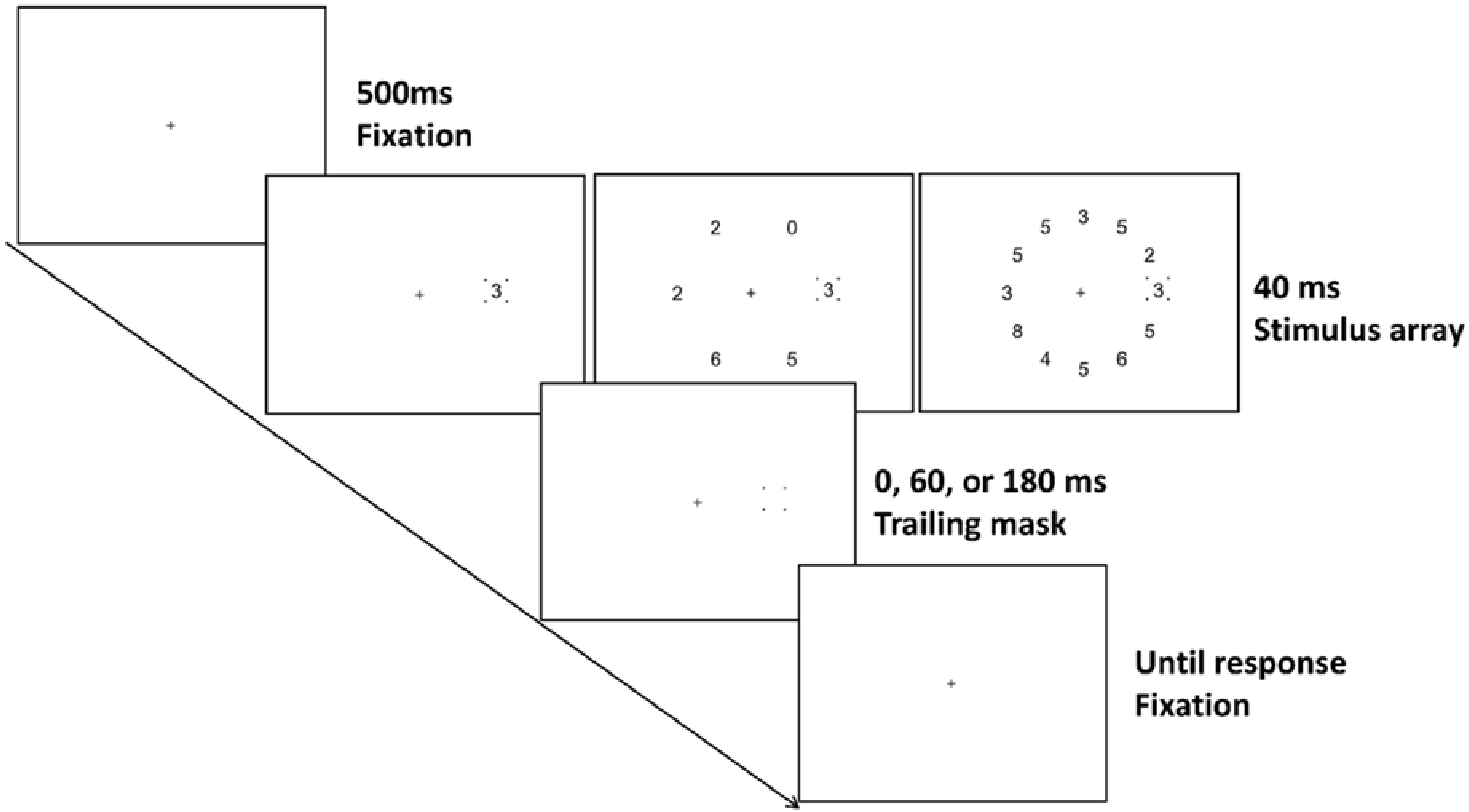

Figure 4| A schematic depiction of the trial sequence in Experiment 1 (digit identification

Results

The average percent correct responses in each factorial condition of mask duration and set size are shown in Figure 5(A). These data were analysed using a repeated measures ANOVA with two factors, each with three levels: *set size* (1, 6, and 12) and *mask duration* (0, 60, and 180ms). There were significant main effects of *set size*, $F(2, 32)=217.16$, $MS^{error}=25.53$, $p<.001$, $\eta_p^2=.93$, and *mask duration*, $F(2, 32)=125.30$, $MS^{error}=24.58$, $p<.001$, $\eta_p^2=.89$. Importantly, a significant interaction was also produced between *set size* and *mask duration* $F(4, 64)=17.56$, $MS^{error}=17.56$, $p<.001$, $\eta_p^2=.52$. Examination of Figure 5 indicates that the interaction resulted from the fact that masking (as indexed by mask duration) increased with set size.

Simple effects t-tests were conducted on the accuracy data and revealed that set size affects performance even in the absence of OSM. There was a significant difference in performance between a set size of 1 and 6 ($t[16]=5.45$, $p<.001$) and 1 and 12 with a 0ms mask duration ($t[16]=4.76$, $p<.001$). There was no significant difference in performance between a set size of 6 and 12 at a 0ms mask duration however ($t[16]=0.66$, $p=.519$). Further simple effects t-tests revealed that OSM was produced even for a set size of one. There was a significant difference in performance between a 0ms and a 60ms mask duration ($t[16]=5.38$, $p<.001$), a 60ms and a 180ms mask duration ($t[16]=4.01$, $p=.001$) and 0ms and a 180ms mask duration ($t[16]=9.48$, $p<.001$).

However caution must be exercised in interpreting interactions based on ANOVA analysis of the raw percentage scores as percent correct is essentially a probabilistic measure. Independent probabilities sum according to a multiplication rather than an addition rule. Thus if two variables are statistically independent their aggregate effect on a probability measure (such as percent correct) will be multiplicative. This means that the presence of a statistical interaction should not be taken as evidence of the dependence of two variables when the dependent variable is raw accuracy. The standard way to deal with this issue is to perform the analysis on transformed scores. It has been shown mathematically that, after log transformation independent effects sum additively (see Schweickert, 1985, for a mathematical proof of this).

Thus for these data (and the other experiments in this thesis where the dependent variable was a percent correct measure) the ANOVA analysis was repeated and presented using transformed (log10) accuracy scores (a similar procedure to that conducted by Filmer et al., 2014). This transformation did not markedly change the basic pattern of the data (see Figure 5, plate B), and, importantly, the significant interaction between set size and mask duration was retained, $F(4, 64)=28.60$, $MS^{error}=0.01$, $p<.001$, $\eta_p^2=.64$. Thus, Experiment 1 clearly demonstrates that the strength of masking in OSM (as indexed by the effect of mask duration) was influenced by set size under the conditions given.

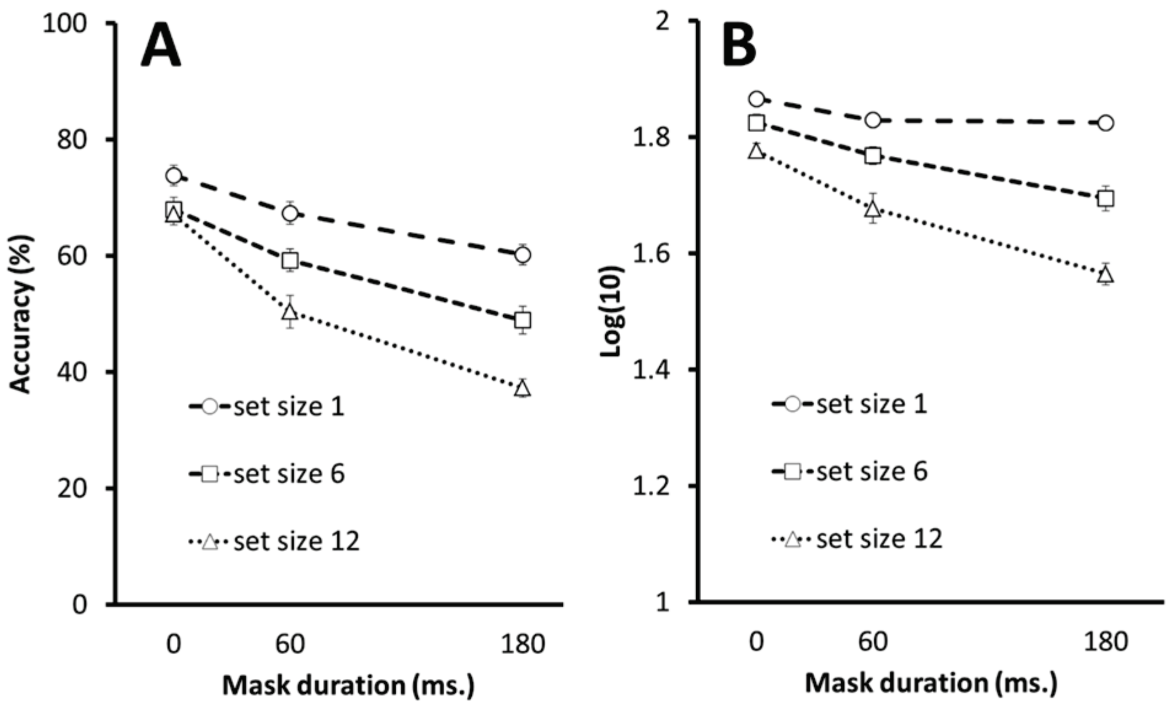

Figure 5| Performance in Experiment 1 (digit identification task). Accuracy (% correct [panel A]) and transformed accuracy (log10 [panel B]) are shown for the three set sizes (1, 6, 12) by each mask duration condition (0, 60, 180ms). Error bars represent +/-1 standard error of the mean.

Discussion

This interaction between set size and mask duration is inconsistent with the reported results of both Argyropoulos et al (2013) and Filmer et al (2014). It is, however, quite consistent with the original findings reported by Di Lollo et al (2000). Unlike the data of Di Lollo et al however this interaction cannot easily be explained as an artifact of constraints in the measurement of performance. In all conditions participants were well below ceiling (the maximum score in any condition was 83.3%, the minimum 28.3%). This finding is in line with that of Pilling (2013) in which set size was found to increase masking magnitude irrespective of constrained performance. One aspect of this current data was consistent with both Argyropoulos et al and Filmer et al however: the presence of distractors was wholly unnecessary for OSM to be observed. It can be seen in the graphs (Figure 5) that even with a set size of 1 (target alone) there was a clear effect of mask duration. What is different from the findings of Argyropoulos et al and Filmer et al however is that the addition of distractor items did augment the effect of the trailing mask on performance (note the steeper lines for set size 6 and 12). This finding of a significant interaction is arguably unexpected based on the previous literature by Argyropoulos et al and Filmer et al. This finding is in contrast to these two recent studies, including one study conducting in the same lab as the current experiment. The question, in this case, is why these results differ so dramatically.

One clear difference between the current experiment and those of Argyropoulos et al (2013) and Filmer et al (2014) is the number of response options available. The identification task in the current experiment used a 10-alternative forced choice task (i.e. respond to the digit's identity from 0-9). This can be contrasted with the 4-alternative forced choice response (and in the case of one experiment, a 2-alternative forced choice response) task used by Argyropoulos et al. It is therefore possible that this greater number of response options increased the level of complexity in the perceptual decision process associated with identifying the target digit. This presumed increase in time required to process the stimulus and determine its identity from amongst the 10 possibilities could, somehow, make the task more sensitive to set size effects. If this is the case the interaction between set size and mask duration should dissipate when a 4-alternative forced choice version of the digit identity task is used.

2.3 Experiment 2: Digit identification (4AFC) task

Experiment 2 was conducted as a 4-alternative forced choice (4AFC) replication of Experiment 1. If the set size effect was purely a consequence of the task complexity with regards to the response options then conducting the same experiment using 4 response options should abolish or at least diminish the interaction between set size and mask duration which was observed in Experiment 1. If however, the interaction is replicated in this experiment it would rule out the more complex nature of the perceptual decision in Experiment 1 as a factor in producing the effect of set size in OSM. It was therefore expected that no interaction would be produced between set size and mask duration using a 4AFC task.

Method

Participants

Nineteen participants (13 female) from the Oxford Brookes Psychology student panel took part in the experiment. All participants gave informed consent and received course credits for completing the experiment. All participants reported normal or corrected-to-normal visual acuity.

Stimuli and procedure

Stimuli and procedure were identical to those used in Experiment 1 (see section 2.2). However, the number of digits was reduced to the last four digits on the keyboard (7, 8, 9, and 0). There were 560 trials presented in a random order, 60 trials were given for each combination of mask duration and set size. The experiment was presented in 10 blocks, each of 56 trials. The computer prompted the participant to have a brief break at the end of each block.

Results

The average percent correct responses for each factorial condition of mask duration and set size are shown in Figure 6(A). As with Experiment 1 these data were analysed using a two-way (3x3) repeated measures ANOVA. This analysis showed that there was a significant main effect of *mask duration*, $F(2, 36)=49.81$, $MS^{error}=47.80$, $p<.001$, $\eta_p^2=.74$. Mauchly's test indicated that the assumption of sphericity was violated for *set size*, therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity. The results showed a significant main effect of set *size*, $F(1.32, 23.80)=90.30$, $MS^{error}=62.65$, $p<.001$, $\eta_p^2=.83$. There was also a significant interaction between *mask duration* and *set size* $F(4, 72)=4.85$, $MS^{error}=45.92$, $p=.002$, $\eta_p^2=.52$. As with Experiment 1 the percent correct accuracy data were log transformed (log 10) and produced the same basic data pattern (see Figure 6, plate B).

Simple effects t-tests were conducted on the accuracy data. Given the multiple comparisons the alpha level was adjusted to .017. These simple effects t-tests revealed that OSM was produced even for a set size of one. There was a significant difference in performance between a mask duration of 0 and 60ms ($t[18]=4.20$, $p=.001$) and between a mask duration of 0 and 180ms ($t[18]=4.22$, $p=.001$). There was no significant difference between a mask duration of 60 and 180ms ($t[18]=0.63$, $p=.535$) indicating that strong OSM was present with a 60ms mask. Further simple effects t-tests revealed that set size affects performance even in the absence of OSM. There was a significant difference in performance between a set size of 1 and 6 (t[18]=3.26, *p*=.004) and 1 and 12 (t[18]=3.94, *p*=.001) at a mask duration of 0ms. There was no significant difference between a set size of 6 and 12 however (t[18]=2.24, *p*=.038).

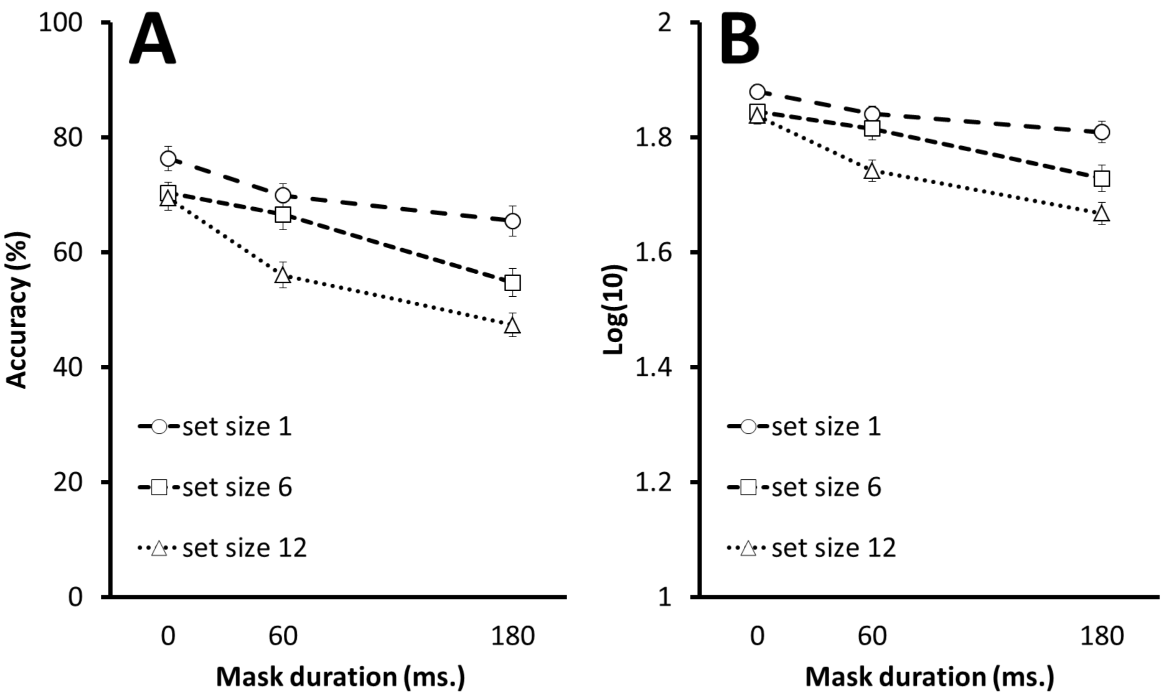

Figure 6| Performance in Experiment 2 (4 digit identification task). Accuracy (% correct [panel A]) and transformed accuracy (log(10) [panel B]) are shown for the three set sizes (1, 6, 12) by each mask duration condition (0, 60, 180ms). Error bars represent +/-1 standard error of the mean.

Discussion

This experiment showed the same pattern of results as Experiment 1. This suggests that the interaction found in Experiment 1 was not purely a consequence of increased task complexity compared to earlier experiments (e.g. Argyropoulos et al., 2013). Given the inconsistency in this regard, it seemed necessary to perform a further study to determine if the interaction would be repeated under different task conditions. Argyropoulos et al (2013) also conducted two target detection tasks. An interaction was produced in only one of these experiments. This interaction was however a consequence of response bias. Response bias was so high that target absent responses were very infrequent causing them to be outside a measurable range when a guessing correction was applied. Once response bias was taken into account, the interaction between set size and mask duration disappeared. A third experiment was therefore conducted in which the task was to *detect* rather than *identify* the target digit.

2.4 Experiment 3: Digit detection task

Experiment 3 was essentially the same as Experiment 1 in terms of the display sequence. The main difference was in terms of what was present at the target location. In Experiment 1 (and 2) a digit was present at the target location (inside the four dot mask) on every trial. In Experiment 3 a digit was present inside the mask on only half the trials; on the others there was a blank space inside the mask. Participants had to make a present or absent response judgement regarding whether they perceived a digit at the mask location. Pilot work showed that performance was at or near ceiling with the stimulus duration used in Experiment 1

(40ms); therefore Experiment 3 also had a briefer stimulus array presentation consisting of just a single refresh of the monitor (10ms).

Experiment 3 served to test whether the results found in Experiment 1 and 2 were in some way specific to the digit identity task, or whether they could also be obtained under different task demands, those of stimulus detection. The interaction between set size and mask duration was therefore examined using a detection task to see if the effect is replicable across task type. It was expected, given the previous findings by Argyropoulos et al (2013) that no interaction between set size and mask duration would be produced under these conditions.

Method

Participants

Fifteen participants (7 female) took part in the experiment. All participants gave informed consent and received £7 remuneration for completing the experiment. All participants reported normal or corrected-to-normal visual acuity.

Stimuli and procedure

The stimulus sequence is shown in Figure 7. Participants were required to report whether or not there was a target digit present within the 4DM using a corresponding key (Z or M) on the computer keyboard. Three *set size* conditions were given (1, 6, or 12), and the trailing *mask duration* was 0, 60 or 180ms as in Experiment 1. The conditions of set size refer to the number of items on target present trials (on target absent trials the set size was one less (i.e. 0, 5, or 11). There were 1080 experimental trials. The target digit was present on 50% of all trial types. Equal numbers of trials were given for each of the 18 factorial combinations of conditions. On trials in which a target digit was present each of the ten digits were shown with equal frequency within each factorial combination. The identity of the distractor digits was random. A demonstration and practice trials were given as in the previous experiments. Participants were instructed to emphasise accuracy in responding.

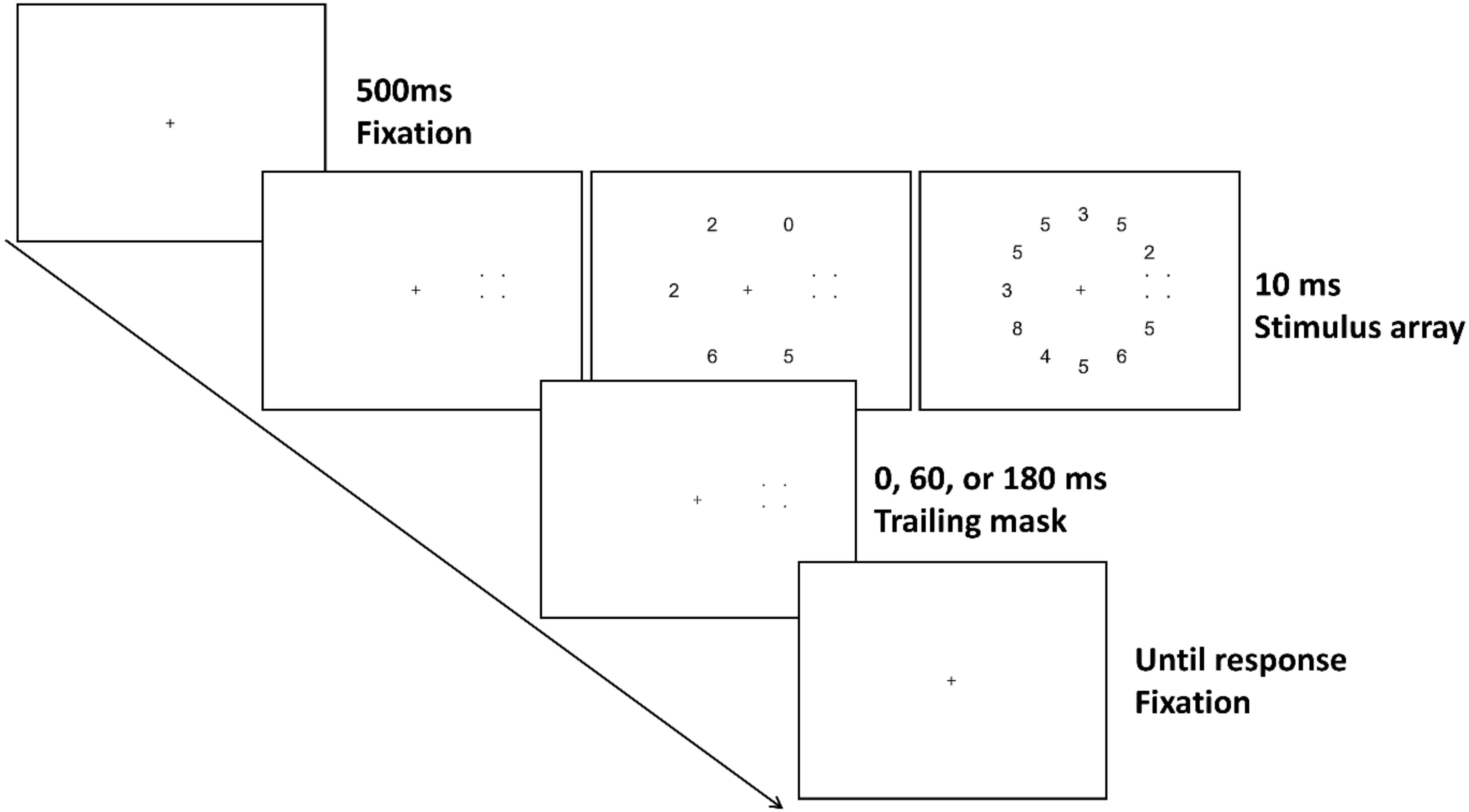

Figure 7| A schematic depiction of the trial sequence in Experiment 3 (digit detection task). Example of a target absent trial shown. On target present trials a digit would be present within the four dots, as in Figure 4.

Results

The proportion of hits (*pHit*) was calculated for target present trials and the proportion of false alarms (*pFA*) on target absent trials (see Figure 8, plates A and B respectively). From these data a signal detection measure (d-prime [d']) was calculated (Figure 8, plate C), as was a measure of response bias (criterion; C; Figure 8, plate D). d' is a sensitivity index which indicates the separation between the distribution of signal and noise in the data and criterion is a measure of response bias (MacMillan & Creelman, 2005).

ANOVA analysis concentrated on the d' scores. It can be seen that performance decreased as both set size and mask duration increased; the lowest performance levels occurred at a set size of 12 and a mask duration of 180ms. A 2-way repeated measures ANOVA of d' revealed a significant main effect of *set size* ($F[1.36, 19.02]=21.26$, $MS^{error}=0.23$, $p<.001$, $\eta_p^2=.60$) and *mask duration* ($F[1.28, 19.92]=9.13$, $MS^{error}=0.38$, $p=.001$, $\eta_p^2=.40$; using a Greenhouse-Geisser correction), with performance decreasing as set size and mask duration independently increased. A significant interaction was also found between *set size* and *mask duration* ($F[4, 56]=4.58$, $MS^{error}=0.19$, $p=.003$, $\eta_p^2=.25$), reflecting the fact that mask duration had a progressively greater effect with increasing set size.

Simple effects t-tests were conducted on the d' data and revealed that OSM was produced even for a set size of one. There was a significant difference in performance between a mask duration of 0 and 60ms ($t[14]=4.77$, $p<.001$), a mask duration of 0 and 180ms ($t[14]=7.39$, $p<.001$) and a mask duration of 60 and 180ms ($t[14]=2.85$, $p=.013$) when the target was presented alone in the display. Further simple effects t-tests again revealed that set size affects performance even in the absence of OSM. There was a significant difference in performance between a set size of 1 and 6 ($t[14]=3.66$, $p=.003$) and 1 and 12 ($t[14]=2.92$, $p=.011$) at a mask duration of 0ms. However, there was no significant difference in performance between a set size of 6 and 12 ($t[14]=0.73$, $p=.476$).

A further analysis was performed on the C (response bias) data. A two-way ANOVA was performed in the same manner as for the *d'* scores described above. The main effect of *set size* approached significance ($F[2, 28]=3.17$, $MS^{error}=0.14$, $p=.057$, $\eta_p^2=.19$), there was a clear main effect of *mask duration* ($F[2, 28]=36.83$, $MS^{error}=0.16$, $p<.001$, $\eta_p^2=.73$); no interaction was found between the two factors, ($F[4, 56]=1.05$, $MS^{error}=0.04$, $p=.390$). Thus these data show a tendency for observers to shift from a moderately conservative to a moderately liberal criterion as mask duration increases. In other words, with increased mask duration observers showed a greater tendency to *report* there was something present (irrespective of whether or not there was anything at the target location). As set size was increased a similar criterion shift towards a more liberal criterion was also observed but to a lesser extent.

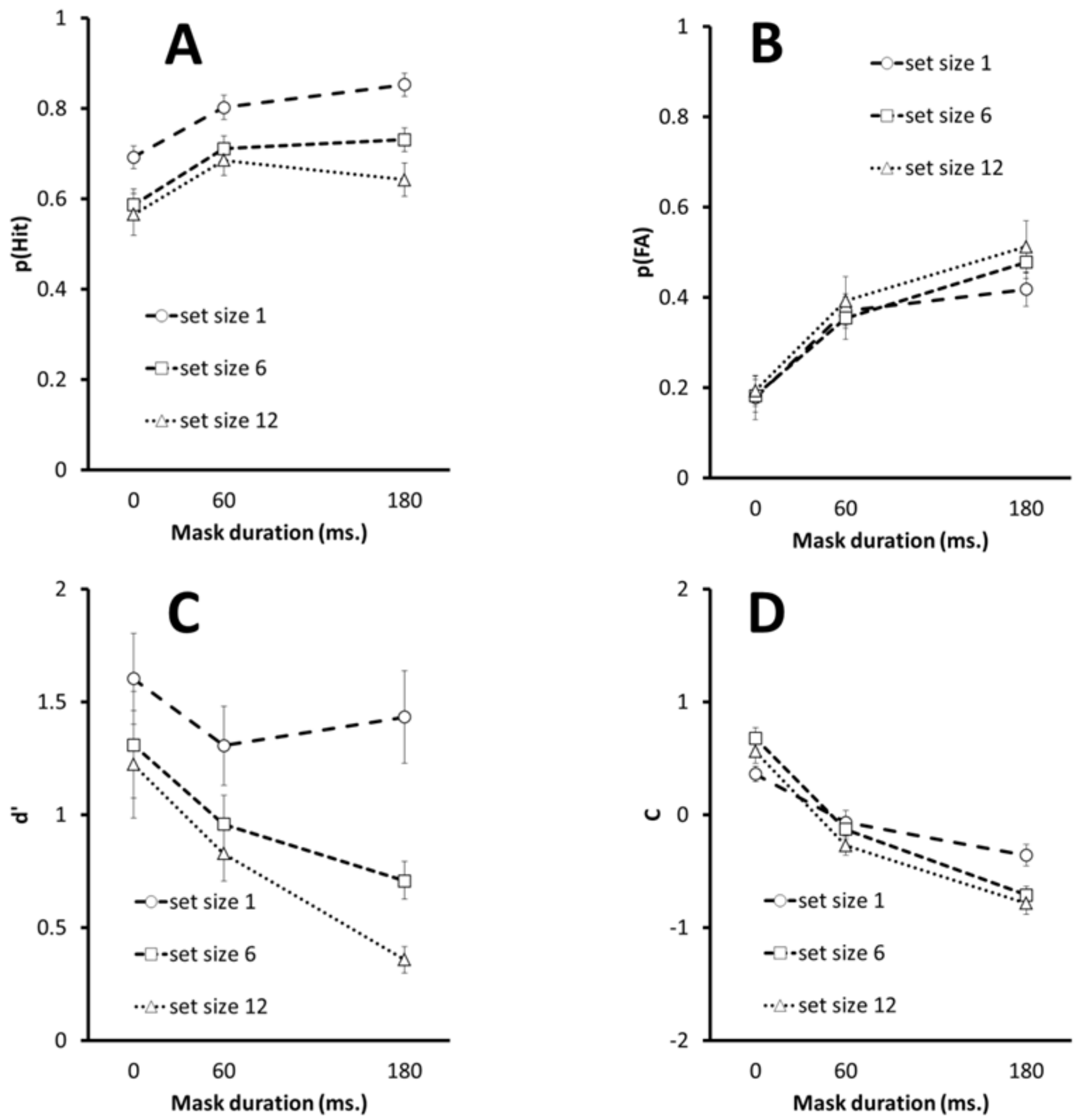

Figure 8| Performance in Experiment 3 (digit detection task). Proportion of hits (p[*Hit*]), proportion of false alarms (p[*FA*]), d-prime (*d'*) and response bias (*C*) are shown in plates A, B, C and D respectively. Error bars represent +/-1 standard error of the mean.

Discussion

An interaction between set size and mask duration was found for the target detection task just as for the digit identification tasks. Importantly this interaction in detection accuracy could not be explained as the consequence of a ceiling effect nor of response bias as it was found with a signal detection measure. Thus again the results are inconsistent with the findings reported by Argyropoulos et al (2013).

It is worth noting that the criterion data displayed an interesting pattern. It seems that the effect on the observer of increasing mask duration (and–to a much lesser extent–of increasing set size) was to produce a criterion shift towards more liberal responding (from a baseline which showed a mild tendency towards conservatism in responding). That is, observers became increasingly likely to report a target as present – even on target absent trials – the longer the mask lingered on screen (or the more items were present in the display). A similar criterion shift was noted (but not formally analysed in the way done here) by Argyropoulos et al (2013) in their line detection task. However the phenomenal consequences of OSM have yet to be systematically investigated in any formal way (though see Koivisto, 2012 for one approach to measuring the subjective consequences of OSM using confidence ratings).

Nevertheless this response bias is not of principle interest for this investigation. Rather, the interaction between set size and mask duration is of importance here. This study has produced for the third time results that are inconsistent with that of Argyropoulos et al (2013) and Filmer et al (2014). These results show that the interaction between set size and mask duration is not task specific as it has now been consistently produced across identification and detection tasks.

It is possible that this pattern of results relates specifically to the use of digits as stimuli. Digits are a special class of stimuli in that, for most observers, they are heavily overlearned. Overlearned stimuli have sometimes been found to produce different patterns of results from other stimulus types on attentional tasks (e.g. Kawahara, Zuvic, Enns & Di Lollo, 2003; Martens, Korucuoglu, Smid & Neuwenstein, 2010; Rotte, Heinze & Smid, 1997). It is therefore possible that the observed set size effect on masking has something to do with this attribute of digits as stimuli.

2.5 Experiment 4: digit familiarity task

In order to assess this overlearned aspect of digits a study consisting of two sub-experiments (a, b) was conducted using upright and inverted digits. The unfamiliar orientation of inverted digits has been shown to disrupt processing (Corballis, Zbrodoff, Shetzer & Butler, 1978). This should enable a direct comparison with the previous studies conducted in this series. If an interaction fails to be to be produced in this experiment, it would suggest that there is something fundamentally different about the processing of digits and their familiarity that makes them more susceptible to masking than the sorts of Landolt stimuli used in Argyropoulos et al (2013) and Filmer et al (2014). It was therefore expected that an interaction between mask duration and set size would be produced for the upright digit experiment (4a). However importantly, it was expected that this interaction would not be replicated for the inverted digit experiment (4b).

The number of digits used in this study was reduced to five (2, 3, 4, 5, and 7). This subset of digits were chosen specifically because they appear distinctly different in their inverted form (compared to, for instance, “0”, “8” and “1” which respectively appear identical or almost identical when inverted, and “6” and “9” which look the same when inverted.

Method

Participants

Twenty-seven participants (26 female) from the Oxford Brookes Psychology student panel took part in the experiment. All participants gave informed consent and received course credits. All participants reported normal or corrected-to-normal visual acuity.

Stimuli and procedure

Stimuli and procedure were identical to those used in Experiment 2 (see section 2.3) except as mentioned in the introduction regarding the digits used. In sub-experiment B, the digits were the inverted form of the digits presented in sub-experiment A. There were 540 randomly ordered trials, 60 trials for each combination of mask duration and set size. The experiment was presented in 10 distinct blocks. The computer prompted the participant to have a brief break after each 54 trial increment.

Results

Experiment 4a

The average percent correct responses in each factorial condition of mask duration and set size are shown in Figure 9(A). The data were analysed using a two-way repeated measures ANOVA. There was a significant main effect of *mask duration*: $F(2, 22)=29.22$, $MS^{error}=81.82$, $p<.001$, $\eta_p^2=.73$ and *set size*: $F(2, 22)=51.70$, $MS^{error}=84.24$, $p<.001$, $\eta_p^2=.83$. There was also a significant interaction between *mask duration* and *set size* $F(4, 44)=6.49$, $MS^{error}=35.39$, $p<.001$, $\eta_p^2=.37$. These results are in line with the previous findings in this series, and as expected, show that increased set size leads to increased OSM. As with the previous experiments that have used accuracy data, log(10) transformation was conducted and yielded the same pattern of results (see Figure 9, plate B).

Simple effects t-tests were conducted on the accuracy data. Given the multiple comparisons being made the alpha level was corrected to .017. These simple effects t-tests revealed that OSM was not produced for a set size of one. There was no significant difference in performance between a mask duration of 0 and 180ms (t[11]=2.25, *p*=.046), 0 and 60ms (t[11]=1.61, *p*=.135) or 60 and 180ms (t[11]=0.82, *p*=.429) when the target was presented alone in the display. Further simple effects t-tests revealed that set size affects performance even in the absence of OSM. There was a significant difference in performance between set size 6 and 12 (t[11]=4.95, *p*<.001) and 1 and 12 (t[11]=4.62, *p*=.001) at a mask duration of 0ms. There was no significant difference in performance between a set size of 1 and 6 (t[11]=1.81, *p*=.097).

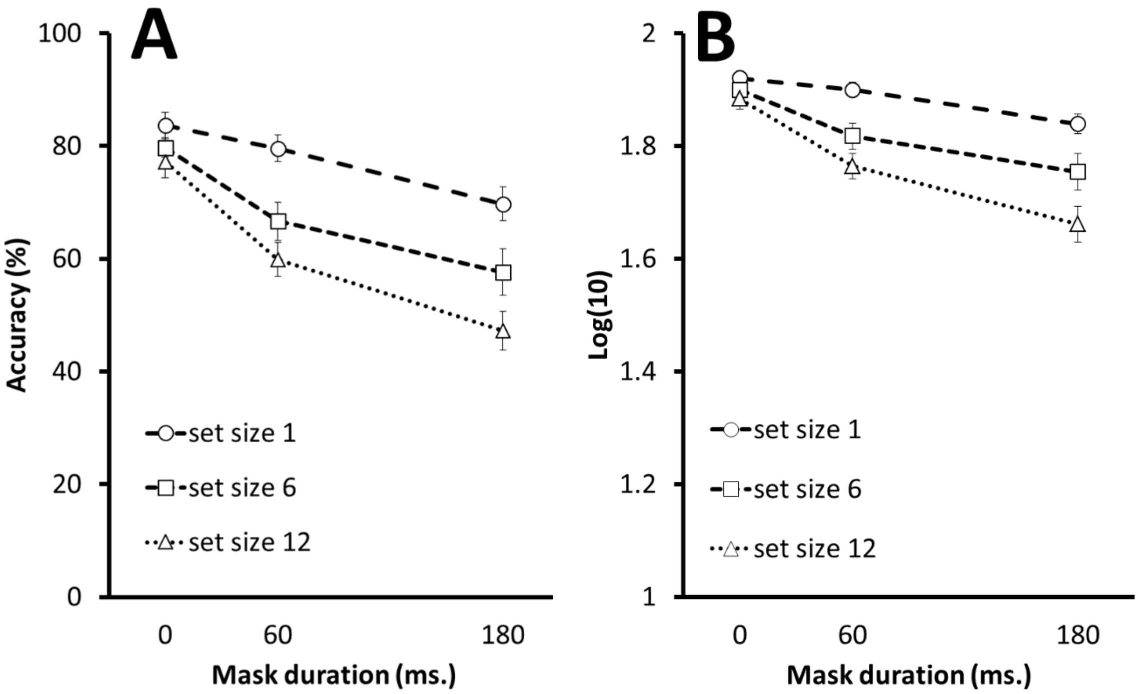

Figure 9| Performance in Experiment 4a (upright digit identification task). Accuracy (% correct [panel A]) and transformed accuracy (log(10) [panel B]) are shown for the three set sizes (1, 6, 12) by each mask duration condition (0, 60, 180ms). Error bars represent +/-1 standard error of the mean.

Experiment 4b

The average percent correct responses in each factorial condition of *mask duration* and *set size* are shown in Figure 10(A). The data were analysed using a two-way repeated measures ANOVA. There was a significant main effect of *mask duration* (using the Greenhouse-Geisser correction) and *set size* respectively: $F(1.30, 18.48)=23.34$, $MS^{error}=63.98$, $p<.001$, $\eta_p^2=.63$ and $F(2, 28)=36.29$, $MS^{error}=73.39$, $p<.001$, $\eta_p^2=.72$. There was also a significant interaction between *mask duration* and *set size,* $F(4, 56)=5.52$, $MS^{error}=28.10$, $p=.001$, $\eta_p^2=.28$. These results are in line with those found in Experiment 4a indicating that set size does indeed have an effect on OSM. Again, log(10) transformation was conducted but this did not affect the pattern of results (see Figure 10, plate B).

Simple effects t-tests were conducted on the accuracy data. Given the multiple comparisons the alpha level was adjusted to .017. The simple effects t-tests revealed that OSM was not produced for a set size of one. There was no significant difference in performance between a mask duration of 0ms and 60ms ($t[14]=2.07$, $p=.057$), 0ms and 180ms ($t[14]=1.94$, $p=.073$) and 60ms and 180ms ($t[14]=0.12$, $p=.905$) when the target was presented alone in the display. Further simple effects t-tests revealed that set size affects performance even in the absence of OSM. There was a significant difference in performance between set size 1 and 6 ($t[14]=3.33$, $p=.005$) and 1 and 12 ($t[14]=3.07$, $p=.008$) at a mask duration of 0ms. There was however no significant difference between a set size of 6 and 12 ($t[14]=1.02$, $p=.327$).

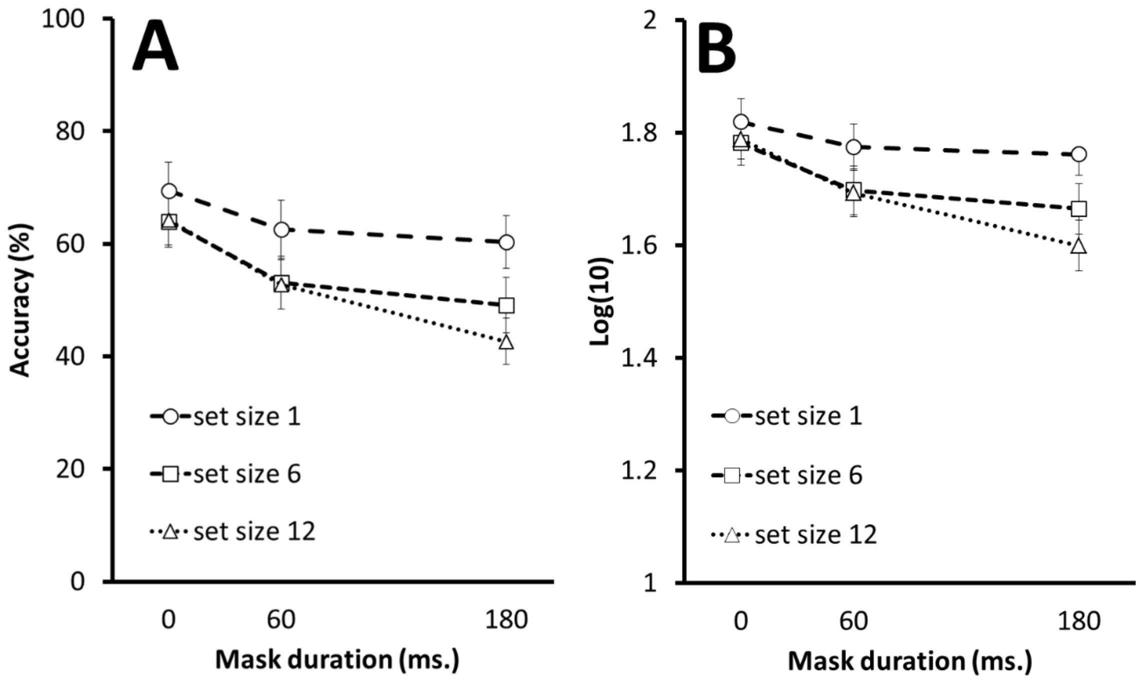

Figure 10| Performance in Experiment 4b (inverted digit identification task). Accuracy (% correct [panel A]) and transformed accuracy (log(10) [panel B]) are shown for the three set sizes (1, 6, 12) by each mask duration condition (0, 60, 180ms). Error bars represent +/-1 standard error of the mean.

Comparisons between Experiment 4a and 4b

A three-way mixed ANOVA was conducted with *mask duration* (0, 60, 180ms; within-subjects), *set size* (1, 6, 12; within-subjects) and *stimulus presentation* (upright, mirrored; between-subjects). There was a significant difference in performance across parts a and b of Experiment 4 ($F[1, 25]=4.74$, $MS^{error}=1658.76$, $p=.039$, $\eta_p^2 =.16$). As can be seen in Figures 9 and 10, this indicates identification performance tended to be lower with the inverted digit manipulation showing that the visual system was less efficient in identifying the digits in the (unfamiliar) inverted form. However, importantly this orientation manipulation had no effect on masking ($F[2, 50]=2.25$, $MS^{error}=103.61$, $p=.135$, using the Greenhouse-Geisser correction). There was also no significant three way interaction between mask duration, set size and orientation ($F[4, 100]=1.04$, $MS^{error}=34.16$, $p=.389$, using the Greenhouse-Geisser correction.

Discussion

The first point to note is that inverting the digits did affect their perceptibility. Accuracy was lower for the digits when presented in inverted form. Nevertheless, the results of these studies again showed an interaction between set size and mask duration irrespective of the orientation (and thus presumably the familiarity) of the digit stimuli. Furthermore there were no interactions between digit orientation and any of the other variables in the experiment. Thus though familiarity influenced identification accuracy it did not seem to affect masking nor be a factor which determined the relationship between set size and mask duration. This suggests that the effect of set size produced in the previous experiments is, contrary to what was predicted, not a consequence of the overlearned nature of digits as a stimulus class.

So why then do the results with digits repeatedly show an interaction? Another possible factor that may underlie the difference in these results with those of Argyropoulos et al (2013) and Filmer et al (2014) is that the stimuli are more heterogeneous as a class than those in the earlier investigations. The individual digits in the current experiments are certainly far more perceptually varied from one another in terms of their contained features than the circles with a vertical bar or the Landolt stimuli used in Argyropoulos et al (2013) and Filmer et al (2014). Possibly it is the heterogeneity of the stimulus display that is the factor which determines whether or not set size interacts with masking. Experiment 5 tested this possibility by using homogeneous Landolt stimuli, with the stimulus dimensions and viewing conditions used in Experiments 1-4.

2.6 Experiment 5: Landolt square task

Experiment 5 was designed as a replication of Experiment 1, except for the fact that Landolt squares were used for identification in replacement of digits. The Landolt squares were the same height as the digits used in Experiment 1 and were presented on a virtual array of the same diameter as Experiment 1. Participants had to report the missing side of the target Landolt square defined in the array by the surrounding 4DM. It was expected that when this more simple stimulus class was used, an interaction between set size and mask duration would not be produced.

An initial Landolt experiment was conducted in exactly the same manner as the one presented here except with a smaller gap (0.21°). For the first time in this series of experiments an interaction was not observed between set size and mask duration, replicating the finding of Argyropoulos et al (2013). However, during analysis it became evident that this was potentially a consequence of constrained performance (particularly in the masked conditions at the higher set size(s) and in the participants with below median overall performance). The second Landolt square experiment (presented below) was therefore conducted with an increased gap size in order to move performance to within a measurable range.

Method

Participants

Sixteen participants (16 female) from the Oxford Brookes Psychology student panel took part in the experiment. All gave informed consent and received course credits for completing the experiment; all reported normal (or corrected-to-normal) visual acuity.

Stimuli and procedure

The manner and procedure of the experiment were the same as Experiment 1 (see section 2.2) except for the stimuli being Landolt squares rather than digits. Participants were required to report which side of the target had a missing segment using one of the four arrow keys on a conventional keyboard. The Landolt squares were 0.52° of visual angle in width and height respectively. The missing segment was 0.31° in size (see Figure 11). There were three *set sizes* (1, 6, and 12) and three *mask duration* conditions (0, 60, and 180ms) factorially combined as in the previous experiments. Participants were given a demonstration and practice trials as in previous experiments. There were 540 experimental trials. The target gap position occurred equally often in each of the four cardinal positions in the experiment within each of the nine factorially combined conditions. The gap position in the distractor stimuli was randomly determined for each stimulus.

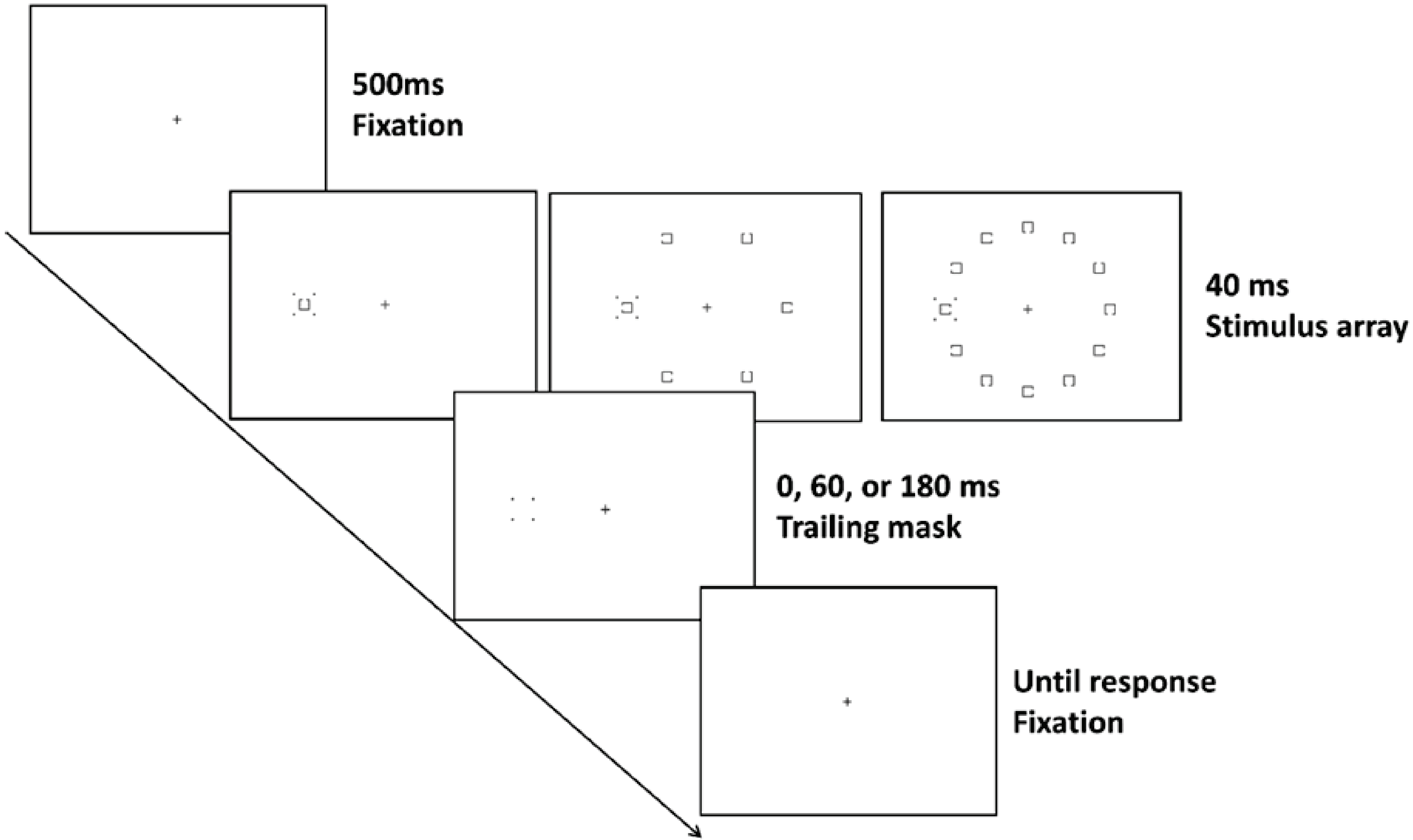

Figure 11| A schematic depiction of the trial sequence in Experiment 5 (Landolt square discrimination task).

Results

Mean percent correct data for each combination of *set size* and *mask duration* were examined and are shown in Figure 12. The data were analysed using a two-way repeated measures ANOVA. The results showed a significant main effect of *mask duration* and *set size* respectively: F(1.49, 23.76)=34.28, MS^{error}=103.27, *p*<.001, η_p^2=.68 and F(1.43, 22.89)=55.67, MS^{error}=117.09, *p*<.001, η_p^2=.78 (both using the Greenhouse-Geisser correction). Importantly, again there was a significant interaction between *mask duration* and *set size*: F(4, 64)=4.78, MS^{error}=30.61, *p*=.002, η_p^2=.23. However it is possible that the interaction observed here reflects constraints in measureable performance due to ceiling effects, rather than being a genuine interaction. Indeed one participant was at 100% in the 0ms condition of set size 1. To test this, following the procedure adopted in Filmer et al (2014) in their Experiment 1 where a similar problem was encountered, the analysis of the interaction was repeated, but this time including only set sizes 6 and 12. The same pattern of significance was obtained including the set size×mask duration interaction (F[2, 30]=3.68, MS^{error}=30.86, *p*=.037, η_p^2=.20).

Simple effects t-tests were conducted on the accuracy data. Given the multiple comparisons being made the alpha level was corrected to .017. These simple effects t-tests revealed that OSM was produced even for a set size of one. There were significant difference in performance between a mask duration 0 and 180ms (t[16]=4.44, *p*<.001). However, there was no significant difference between a mask duration of 0 and 60ms (t[16]=2.19, *p*=.044) or 60 and 180ms (t[16]=2.60, *p*=.019). Further simple effects t-tests revealed that set size affects performance even in the absence of OSM. There was a significant difference in performance between set size 1 and 6 (t[16]=3.66, *p*=.002) and 1 and 12 (t[16]=4.21, *p*=.001) at a mask duration of 0ms. There was however no significant difference between a set size of 6 and 12 (t[16]=2.35, *p*=.032).

These data were log transformed to give an additional test of the interaction. This showed a clear significant set size×mask duration interaction ($F[4,6]=6.72$, $MS^{error}=0.02$, $p<.001$, $\eta_p^2=.31$); this interaction remained significant with the log transformed scores even when only the 6 and 12 set size conditions were analysed, $F(2,30) = 3.92$, $MS^{error} = 0.02$, $p = .031$, $\eta_p^2=.21$.

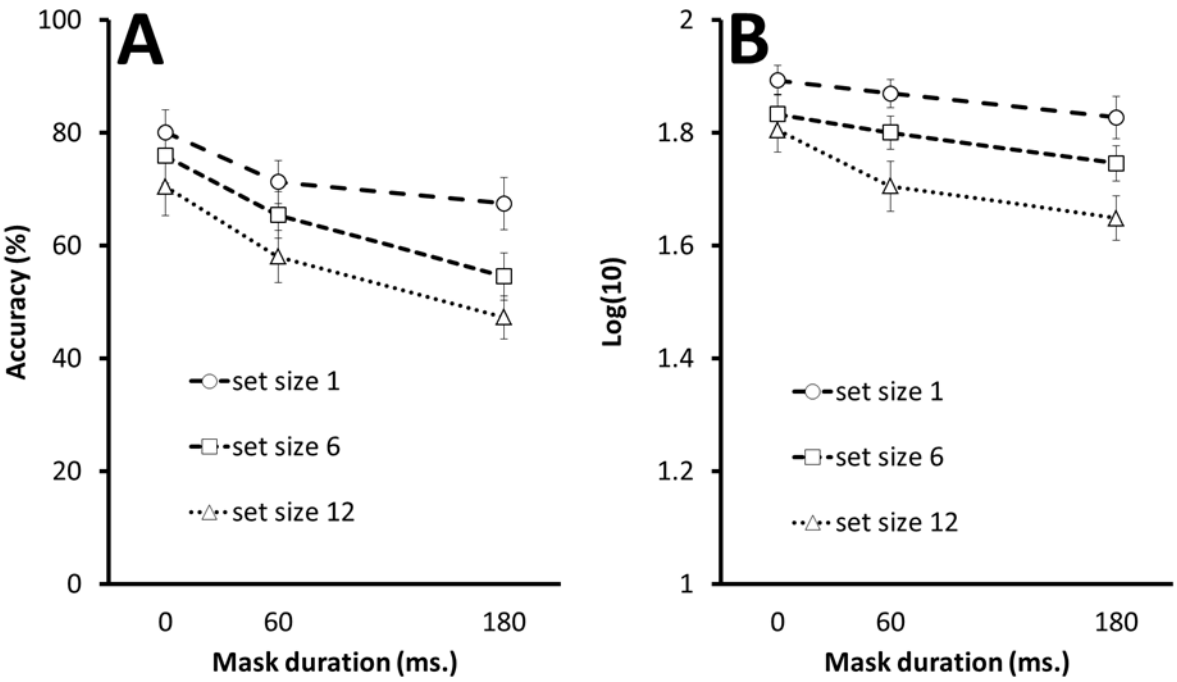

Figure 12| Performance in Experiment 5 (Landolt square discrimination task). Accuracy (% correct [panel A]) and transformed accuracy (log(10) [panel B]) are shown for the three set sizes (1, 6, 12) by each mask duration condition (0, 60, 180ms). Error bars represent +/-1 standard error of the mean.

Discussion

The results of this study showed an interaction between set size and mask duration despite the stimuli not being digits. In this experiment, the interaction was demonstrated using stimuli that closely resembled those used by Argyropoulos et al (2013) and Filmer et al (2014) as well as those used in the original experiments on OSM by Di Lollo and colleagues (2000).

These findings therefore indicate that the interaction between set size and mask duration found in this series has little relation to the heterogeneity of the stimulus display. Rather, the current series of experiments show strong set size effects, even when using simple Landolt objects. As such, these findings present a stark difference to the most recent findings of Argyropoulos et al (2013) and Filmer et al (2014) that set size is not a relevant feature in OSM. The potential reasons for this difference will be raised in the General Discussion.

2.7 General Discussion

Five experiments were conducted in this series to investigate the involvement of set size in OSM. These experiments aimed to explore whether set size is a necessary component of OSM as claimed by the OSTM, or whether this proposed set size effect is a mere artifact of the constrained performance that has been commonly found in OSM experiments previously. Experiment 1 produced an interaction that was not observed in two recent investigations (Argyropoulos et al., 2013; Filmer et al., 2014). This interaction could not be easily explained as a consequence of restricted performance, as was claimed of Di Lollo and colleagues' (2000) data.

The remaining four experiments aimed to understand the discrepancy in findings observed between Experiment 1 in this series and those of Argyropoulos and colleagues (2013) and Filmer and colleagues (2014). That is, these experiments aimed to understand why an interaction was produced in Experiment 1 when recent research had failed to produce an interaction across multiple experiments. Experiments 2-5 scrutinised different experimental factors such as task (identification, detection, discrimination) and stimulus type (digits, inverted digits, Landolt stimuli) in an attempt to understand what underpins the interaction between set size and mask duration in OSM.

These experiments consistently produced a distinct interaction between set size and mask duration, one which in every case persisted even when the data were log transformed (see Schweickert, 1985). In all cases OSM was found to increase multiplicatively with increases in set size. These findings therefore suggest that an interaction between set size and mask duration can in fact still be produced even when performance is clearly within a measurable range (i.e. when ceiling and floor effects are not evident in the data). This indicates that contrary to the suggestion of Argyropoulos et al (2013) and Filmer et al (2014), ceiling and floor effects are not an explanation for the interaction between set size and mask duration in OSM. Thus the set size×mask duration interaction must reflect the operations of processes associated with the distractors which somehow augment the OSM effect.

Although this set of studies produced the interaction between set size and mask duration contrary to Argyropoulos et al (2013) and Filmer et al (2014), they were consistent with their findings in some other respects. The current experiments, as with Argyropoulos et al and Filmer et al, showed that the presence of distractors is not a requirement for OSM to occur. Di Lollo and colleagues (2000) claimed that the presence of distractors was essential to produce OSM. They failed to observe any effect of a trailing mask with a set size of 1 (i.e. target only). It was argued that this was due to the fact that the target was under the focus of attention under these conditions.

In the current series of experiments however, masking was produced even with a set size of 1. This shows that the inclusion of distractors is not essential for producing OSM. Thus, OSM can occur in the absence of competition from other display items, as has been shown most compellingly by Filmer et al (2015). What is in direct contrast to those previously presented studies however is the ability of set size to increase OSM in the current research. Argyropoulos et al (2013) and Filmer et al (2014) both consistently failed to produce any kind of interaction between set size and mask duration once constrained performance had been accounted for.

Interestingly the only time that set size failed to have a visible effect on OSM in the current series of experiments was when performance was constrained by floor effects (see pilot to Experiment 5). It is likely that under these conditions the effect of set size was not apparent in the accuracy data due to the restricted measurement range in the masked conditions. Thus the presence of an interaction would not be revealed in the data under these circumstances. This would indicate that constrained performance, as claimed by Argyropoulos et al (2013), cannot fully explain the interaction between set size and masking in OSM and that in fact, constrained performance (at least in the case of a floor effect) can actually lead to a failure to observe this interaction in the data.

So why is it that in five experiments an interaction was robustly produced when the same interaction was so elusive in the research of Argyropoulos et al (2013) and Filmer et al (2014)? It is possible that there are methodological differences between the two previous sets of studies and the experiments described in this chapter causing such disparate findings. These potential differences will now be explored in more detail by comparing the methods in these earlier papers with those of the current studies.

One possible difference is the stimulus durations used. Filmer et al (2014) used a stimulus display of 100ms. This stimulus display time is unusually long for OSM; it is more than double the longest presentation time used in the current experiments (40ms). Evidence of attenuation of OSM with prolonged target duration has been previously reported (Gellatly et al., 2010). Additionally, the OSTM predicts that OSM should be reduced with long target durations as the likelihood of the iterative cycle being completed becomes increasingly likely (Di Lollo et al., 2000). It is understandable therefore that target perceptibility was greatly increased at this particularly prolonged stimulus display duration. Consequently, strong masking was unlikely to be produced under the conditions presented by Filmer et al. It is arguably unsurprising therefore that they failed to produce an interaction between set size and mask duration. Interestingly, even under these conditions, when scrutinising their data it is evident that it shows trends towards increases in masking with set size. This is particularly evident when their data were log transformed (see esp. their Figure 3) although these trends were non-significant.

When comparing the current experiments with those of Argyropoulos et al (2013) there are two main ways in which their studies differ from those presented in this chapter. Either of these factors could potentially explain the different results. Firstly, the stimuli used by Argyropoulos et al were substantially smaller than those commonly used, and those that were used in this current series of experiments (0.3° compared to 0.47° of visual angle in width and height respectively). There is evidence from other masking literatures to suggest that masking tends to scale with target size (Bachmann, 2000; Breitmeyer & Ogman, 2000). Stimulus size is a factor yet to be examined systematically in the context of OSM. However, it is possible that the increased size of the stimuli in the current experiments compared against Argyropoulos et al facilitated the interaction between set size and mask duration leading to heightened OSM.

Equally, it is possible that due to the smaller target size in the Argyropoulos et al (2013) studies the target was potentially difficult to identify regardless of set size resulting in reduced opportunity for effective masking. Consequently, it is possible that the experiments of Argyropoulos et al were suffering from constrained performance at the lower end. When using the Landolt stimuli in Experiment 5 of the current series it became evident how difficult it was to keep performance within a measurable range when using such a narrow response option task. This is particularly apparent as constrained performance at the lower end caused the interaction between set size and mask duration to be restricted in this series.

In both the current experiments and those of Argyropoulos et al (2013) the stimuli were presented on a notional circle around a central fixation, meaning the stimuli were always at a constant eccentricity. However this stimulus eccentricity tended to be smaller for Argyropoulos et al than it was in the present series of experiments. In most of the experiments in Argyropoulos et al, stimuli were positioned 2.9° radially from fixation; in their Experiment 5, stimuli were positioned only 1.8° from fixation. In all five of the current experiments stimuli were 3.9° degrees from fixation. Thus the stimuli were presented more peripherally in vision. This factor again could explain the discrepancy. Evidence from the literature has suggested that the OSM effect does in fact scale with eccentricity (Di Lollo et al., 2000; Jiang & Chun, 2001). The issue of display eccentricity effects will be returned to in Chapter 3.

Although the present experiments can be taken to support the claims of the OSTM regarding the role of set size in masking (Di Lollo et al, 2000), they do not do so unambiguously. To recap, the OSTM argues that larger set size displays lead to an increased time to contact for the focus of spatial attention to reach the target. Thus, within this model no OSM should be produced at a set size of 1 as the focus of spatial attention is able to be immediately drawn to the target location. As such, the claims made by the OSTM regarding the role of set size in OSM fail to predict that

OSM was repeatedly robustly observed even with a set size of 1 in this series. Other research has raised serious questions over the supposed role of attention in OSM (see discussion of this issue in section 1.6.4 of Chapter 1). If attention, as manipulated by spatial cuing for example (Pilling et al., 2014), does not affect masking then set size (which presumably, like cuing, also affects how attention is distributed towards the target) is also unlikely to influence OSM.

It is therefore possible that the evidence of increased masking with set size in this series had nothing to do with its effect on the distribution of attention but rather with some other process associated with the presentation of additional visual information in the display. It is worth considering that the presence of distractors has been shown to increase internal noise within the visual system (Eckstein, 1998; Magyar, Van den Berg & Ma, 2012; Santhi & Reeves, 2004). Therefore, it is possible, for instance, that increasing the display set size simply increases the internal noise in the visual system during the target presentation, and in doing so somehow makes the target more vulnerable to OSM. Such an explanation is consistent with Põder's (2013) attentional gating theory of OSM (as discussed in section 1.5.2 in Chapter 1) which argues that OSM occurs as a consequence of noise in the visual system generated by the mask. Within this framework it might be argued that the presence of distractors in addition to the trailing mask further adds to this internal noise leading to even greater OSM than would be observed with just the target and mask alone.

However, there is another explanation for the set size×masking interaction that fits with the methodological differences between the current studies and those of Argyropoulos et al (2013). When set size has been investigated in OSM (including in this series), it has tended to be confounded with the spatial proximity of the surrounding distractors to the target. This increased distractor proximity can lead to what has commonly been referred to as "crowding" (Korte, 1923; Pelli, 2008). Crowding occurs when distractors flank a target's location. Target-flanker distance is critical; crowding diminishes with distance and is abolished outside the crowding window. A number of factors have been identified in determining the size of this window and the amount of crowding that will result. A major factor is *eccentricity* (Bouma, 1970; Pelli & Tilman, 2008). With foveated targets crowding is largely absent. However, as a target moves further into the visual periphery crowding effects become more pronounced and the critical spacing becomes proportionally larger (Bouma, 1970).

As described earlier, the stimulus array for the current experiments was more eccentric than in that of Argyropoulos et al (2013). In addition to the increased eccentricity, the stimuli in the current experiments were also larger than those of Argyropoulos and colleagues. Conceivably, the increased size of the stimuli meant that the target was more at risk of crowding. This is because there was a smaller distance between the target and the nearest surrounding distractors. To compound the possible effect of the increase in stimulus size, crowding is known to be most prominent in eccentric displays (Chung, Levi, & Legge, 2001; Levi, 2008; Levi, Hariharan, & Klein, 2002). As such, the possibility for crowding of the target to occur was higher in the present studies. This suggests that there is potential for the target to have fallen victim to crowding.

It is worth mentioning that in the initial description of the OSTM, the possibility of crowding was noted but dismissed as a possible factor in the OSM paradigm. Di Lollo and colleagues (2000) argued that crowding would, at best, only affect overall target perceptibility and its effect would be more modest in size compared with set size. Therefore they claimed that only set size itself, and not crowding, was likely to interact with OSM.

However, given the recent findings against the role of set size in OSM and the fact that crowding of the target could potentially have impacted the current research, this arguably warrants further investigation. What is clear is that distractors do seem to be important in OSM. What is currently unclear however is why distractors have an effect on OSM. The next chapter will therefore aim to separate the effects of set size and crowding in OSM and attempt to look directly at the role of crowding.

2.8 Chapter Summary

The five experiments presented in this chapter set out to explore the interaction between set size and mask duration. The first experiment aimed to examine whether the lack of an interaction between set size and mask duration that has recently been reported (Argyropoulos et al., 2013; Filmer et al., 2014) could be replicated using a likely more complicated stimulus type (digits). This experiment produced an interaction between set size and mask duration for both raw accuracy data and when the data were log transformed. Due to this, the second experiment was conducted to rule out response complexity as a factor that was driving the differing results. As Experiment 1 of this series had 10 response options while previous research has traditionally used a 4 response option task this was deemed as a potential confounding factor. As such, Experiment 2 aimed to examine whether the interaction produced in Experiment 1 was the consequence of increased task complexity by using a 4 response option task. Experiment 2 again produced a reliable interaction between set size and mask duration indicating that this interaction was not caused by the increased perceptual decision making required in Experiment 1.

As the interaction between set size and mask duration was reliably produced across two identification tasks, Experiment 3 was conducted to establish if it was specific to this task type or whether it could be produced across different task demands. Experiment 3 therefore was a target detection version of the paradigm used in Experiment 1. Again an interaction was produced between set size and mask duration for this detection task. At this point, it was evident that the interaction was not related to task demands specifically (e.g. task complexity or response type). This indicated that perhaps it was the stimulus type specifically that was causing the interaction. That is, digits as stimuli are for the most part overlearned and as such have been found to produce a different pattern of results from other types of stimuli (e.g. Rotte et al., 1997).

The fourth experiment in this series was therefore conducted in two parts to assess the effect of this overfamiliarity with digits on OSM. The first part of the experiment was a digit identification task as in Experiments 1 and 2 using 5 response options. The second part of the experiment was an identical identification task except for the fact that the stimuli were inverted digits. If the interaction between set size and mask duration produced in Experiments 1-3 was the consequence of the overlearned nature of digits, differing results would be expected across the two parts of Experiment 4. That is, the interaction between set size and mask duration should be attenuated if driven by overfamiliarity with digits. This was not the case however, and an interaction was produced between set size and mask duration across both parts of the experiment. The only difference between the experiments was an overall reduction in performance with the use of the inverted digits. Thus, the overlearned nature of digits does not seem to be influential in causing the interaction between set size and mask duration.

A final experiment was therefore conducted using the same stimulus type that had been used in the recent studies that failed to find an interaction between set size and mask duration (Landolt figures). This experiment was a replication of Experiment 1 using Landolt squares instead of digits as stimuli. The aim was to better understand the differences that these stimulus classes could possess within the same experimental paradigm. This final experiment again produced an interaction between set size and mask duration. This indicates that the stimuli themselves were not the cause of the differing results between this current series and those of Argyropoulos et al (2013) and Filmer et al

(2014). Rather, the set size effect seems to be clear in the data across this series of experiments irrespective of task or stimulus type. The question now is what the basis of this set size effect is. That is, whether it is due to the spreading of attention and “time to contact” as claimed by the OSTM or whether it is due to the greater proximity of distractors to the target which occurs as set size increases (e.g. crowding of the target) is still in question. This issue will be explored in Chapter 3.

Chapter 3| The role of crowding in object substitution masking

3.1 Introduction

As shown in Chapter 2, a reliable set size effect was found in five experiments. The set size effect was found to occur irrespective of task or stimulus type. However, what is unclear from the results in Chapter 2 is why this set size manipulation had an effect on OSM. This is particularly the case when these findings seemingly contradict some recent published research which seemed to suggest that set size was not a relevant factor in OSM (Argyropoulos et al., 2013, Filmer et al., 2014).

Thus, the experiments in this chapter focus on trying to determine whether “crowding” can explain the nominal set size effect on OSM which was repeatedly observed in all five experiments in Chapter 2. Crowding certainly cannot be ruled out as the relevant factor in influencing OSM: Set size, as investigated in the current series, *always* co-varied with the spatial proximity of the flankers towards the target. That is to say, the more items there were in the display the closer the nearest flankers tended to be towards the target. This confound between set size and crowding is also the case in every other study which has manipulated set size in the context of OSM (e.g. Di Lollo et al., 2000; Jiang & Chun, 2000). Thus it is possible that this increased spatial proximity of the flankers towards the target could lead to crowding, particularly at the larger set sizes.

This chapter will first provide an overview of the crowding phenomenon and describe the underlying mechanisms which have been proposed to account for crowding. The similarities and differences between crowding and OSM will then be detailed before examining how the two phenomena have been combined for investigation in the literature previously. The research undertaken in this chapter will first aim to establish if crowding effects can be produced with the types of displays used in Chapter 2. From this point, whether the effect of set size found in Chapter 2 was a consequence of crowding will be explored. That is, under investigation will be whether crowding rather than set size impacts upon OSM. The extent to which crowding interacts with OSM will then be investigated.

3.1.1 Crowding

Crowding can be defined as the inability to accurately perceive and identify objects when they are in close spatial proximity with other nearby objects (Whitney & Levi, 2011). The first formal description of crowding was given by Korte (1923). In this account Korte described how closely flanking stimuli (consisting of irrelevant letters) negatively affect letter identification. Since this initial description, the classification of crowding has developed to describe the deleterious effect that any surrounding (but non-overlapping) stimulus or stimuli (usually called crowders or flankers) have on the identification of a target (Gurnsey et al., 2011). These crowding effects occur not merely as a construct of artificial laboratory tasks but are also produced in entirely naturalistic scenes, particularly ones which contain large amounts of visual detail (Wallis & Bex, 2012). Furthermore crowding can occur in text and its effects have been observed in reading speeds (Martelli, Di Filippo, Spinelli, & Zoccolotti, 2009; Pelli, Tillman, Freeman, Su, Berger, & Majaj, 2007)

It must be noted that some debate still hinges on the definition of crowding in terms of what phenomena do and do not constitute crowding. Some authors have argued that the term crowding should be narrowly defined and refer only to target-flanker interactions which involve alphanumeric characters (as was the case in Korte's, 1923 studies); such authors tend to argue that *lateral masking* should be used to define "crowding-like" interactions between target and flankers where stimuli are not in this category (e.g. Chung et al., 2001). Most authors however omit the use of lateral masking altogether and use crowding as an omnibus term to describe any interaction between flankers and targets which has a spatial profile and which has a deleterious effect on perception (Levi, Klein & Aitsebaomo, 1985; Parkes, Lund, Angelucci, Solomon & Morgan, 2001). Indeed there is no good reason or evidence to view crowding (as it has narrowly been defined) and lateral masking as being anything other than the same phenomenon. Therefore, within this chapter, the broad definition of "crowding" is employed to refer to all related phenomena.

3.1.2 Hallmarks of crowding

A hallmark of crowding is that it predominantly occurs for targets presented in the visual periphery. Crowding is at best minimal and possibly absent entirely for foveated targets (i.e. ones present at the point of fixation); at the same time crowding effects seem to increase substantially as the target (and flankers) shift away from fixation into the visual periphery (Gurnsey et al., 2011; Huckauf & Heller, 2004; Levi, 2008; Pelli et al., 2004). Thus, crowding is generally considered to be a phenomenon associated with parafoveal vision (Bouma, 1970; Levi & Carney, 2009).

It seems that the spatial extent of crowding not only increases with retinal eccentricity in the parafovea but does so in a lawful manner. There seems to be a systematic relationship between the size of the critical window in which flankers effectively crowd and the eccentricity of the target (Bouma, 1970; Gurnsey et al., 2011). This relationship is referred to as *Bouma's law*; it states that crowding occurs when the separation between the target and distractor is 0.5 or less of the target eccentricity. Moreover, Bouma observed that in peripheral vision *an inward-outward anisotropy* exists for crowding. The crowding effects produced by flankers are not uniform in all directions. Where there is a single flanker its effect is notably stronger when the flanker is more eccentric with respect to the target than when the singleton falls between the target and fixation.

A further hallmark of crowding is its dissociative effect on target detection and identification. Relatively weak crowding is found where the task is to detect whether or not a target is present while substantial crowding is found when the task is to identify what the target is (Pelli et al., 2004). In other words, with a crowded target, the observer can generally tell that a target is present, however they have difficulty identifying *what* that target is. This dissociation has been shown across multiple task types including orientation, contrast, and spatial frequency discrimination, face recognition and with moving flankers (e.g. Andriessen & Bouma, 1976; Bex & Dakin, 2005; Bex, Dakin & Simmers, 2003; Freeman & Pelli, 2007; Louie, Bressler & Whitney, 2007; Põder, 2008; Wilkinson, Wilson & Ellemberg, 1997). Thus, crowding seems most apparent in tasks which require deep perceptual processing, for instance in conjunctive binding tasks where two features of the target have to be identified in conjunction (Pelli et al., 2004).

A final hallmark of crowding is the importance of target-flanker similarity. That is, the target and flankers must be similar in appearance to produce the crowding effect on the target. For instance, in the case of a letter target, crowding is most apparent when the flankers themselves are also letters or have letter-like features; little crowding would be found in this case if the flankers consisted of non-letter like objects (Levi, 2008; Pelli et al., 2004; Xu, 2010). This is also apparent for non-alphanumeric stimuli. For example, with a vernier display (two short abutting lines) strong crowding is produced when flankers are the same length as the vernier and becomes increasingly weaker with increased difference in the length of the vernier and surrounding flankers (e.g. Chicherov, Plomp & Herzog, 2014).

3.1.3 Theories of Crowding

There is as yet no consensus regarding the neurocognitive mechanisms which underlie crowding (Levi, 2008; van den Berg, Roerdink & Cornelissen, 2007). Explanations have generally taken the form of (bottom-up) pooling models or (top-down) attentional models. Bottom up models argue that crowding occurs as a consequence of visual information in the periphery being pooled (neurally) over relatively large spatial regions known as integration fields (e.g., Pelli et al., 2004; Põder, 2006; Wilkinson et al., 1997). One consequence of this pooling is that the spatial resolution of the visual system becomes increasingly coarse with greater eccentricity of visual information in the visual periphery (Desimone & Schein, 1987). It is argued that crowding is more apparent at eccentric locations because of this pooling. The coarse processing of spatial information means that flanker information becomes spatially integrated with that of the target if flankers fall within the critical pooling window. The consequence of this being that the features of the target become difficult to resolve from those of the flankers.

Though the pooling accounts are, debatably, the most widely accepted models of crowding, some theorists argue that crowding is not bottom-up in nature. Top down models argue that crowding is a consequence of the characteristics of attention. These top-down, attentional models are similar to the bottom-up models in assuming that crowding occurs because of poor spatial resolution of the target. However, they depart from the bottom-up explanation in arguing that the integration which occurs is the consequence of the characteristics of an attentional filter ("sustained attentional spotlight") which exists beyond V1 (He, Cavanagh & Intriligator, 1996; Intriligator & Cavanagh, 2001).

In these models it is argued that target identification relies on the ability of the attentional system to isolate (select) the target as an independent object. This is something which is unproblematic for attention to do when the target is in isolation or where flanking items are some distance away. The problem, according to the model, occurs when the target and flankers fall into a region which exceeds the resolution of the attentional spotlight. Under these circumstances the flankers become inadvertently selected by the attentional system along with the target because of the limitations of selection. The consequences of this selection lead to crowding and reduced awareness of the target features. This top-down model can also account for many of the known characteristics of crowding. For instance the fact that crowding scales with eccentricity is explained within this model by the fact that the attentional window broadens with eccentricity (Chakravarthi & Cavanagh, 2007; He et al., 1996; Intriligator & Cavanagh, 2001).

A model proposed by Strasburger (2005) has attempted to reconcile the bottom-up and top-down accounts. This model suggests that both (bottom-up) pooling and (top-down) attentional processes influence crowding in tandem. In the architecture of this model, crowding occurs due to impaired feature integration. This means that the "feature integration field" (i.e. sustained attentional spotlight) is not focused narrowly enough on the target, allowing flankers to become integrated with the target percept. Strasburger demonstrated that spatial pre-cuing of a target's location can provide some protection against crowding, evidence he argued demonstrated a critical role for spatial attention in the crowding phenomenon.

In this model the cue enables spatial attention to be concentrated at the target's location prior to the target onset. The attentional prioritisation which the pre-cued target receives helps protect against integration with the surrounding flankers according to the model. Cuing is argued to increase attention towards the target while having little effect on the extent to which the flankers are also attended. Transient attention is initially drawn towards the target location with the use of the spatial cue. However, depending on the proximity of the flankers they could also be drawn into the sustained attentional spotlight. As such, transient attention (i.e. cuing) can provide attentional prioritisation of the target and potentially facilitate feature integration. However transient attention is not able to protect the target against integration from the surrounding flankers if these flankers fall within the attentional spotlight (Strasburger, 2005). Therefore, additional attentional resources can be directed towards the location of the target but there is no guarantee that distractors will be prevented from being integrated with the target.

3.1.4 Differences between crowding and masking

From the existing literature, it seems clear that crowding (including lateral masking) is quite distinct from *temporal masking* (i.e. the sorts of phenomena discussed in Chapters 1 and 2 of the thesis such as OSM, metacontrast and interruption masking). For instance crowding is largely spatial in nature (Pelli et al., 2004) while masking is thought of as a consequence of the temporal relationship between the target and mask (Di Lollo et al., 2000; Huckauf & Heller, 2004). Additionally, both target detection and identification tasks are heavily affected by masking while crowding, in most circumstances, has little impact on target detection (Di Lollo et al, 2000; Huckauf & Heller, 2004; Lleras & Moore, 2003; Pelli et al, 2004; though cf. Põder 2008).

Crowding is also argued to be dependent on and increase proportionally with eccentricity (Bouma, 1970; Levi, 2008; Pelli et al., 2004). In contrast, masking has been observed to be dependent on, and increase proportionally with, the extent of the mask signal (e.g. mask contrast; Levi, Klein & Hariharan, 2002a; Pelli et al, 2004). Moreover, crowding is most commonly assumed to be based on integration of the target and flanker leading to a "muddled", "confused", or "smudged" percept in which it is hard to determine which features belong to the target and which belong to the flankers surrounding the target (Parkes et al., 2001; Pelli et al, 2004; Tyler & Likova, 2007). Contrary to this, masking commonly results in the complete eradication of the target signal making it hard to determine even whether a target was present or not at the target location (Breitmeyer, 2015; Breitmeyer & Ogman, 2000; Di Lollo et al., 2000; Pelli et al., 2004).

3.1.5 Parallels between crowding and OSM

It is worth noting however that the research to date that has compared crowding and masking has done so exclusively using "classical" forms of masking (Huckauf & Heller, 2004; Pelli et al., 2004). It is questionable therefore whether the differences reported between masking and crowding are relevant to OSM. "Classical" forms of masking such as pattern and metacontrast have been shown to differ substantially from OSM in a number of key ways (as discussed in section 1.4 of Chapter 1; Di Lollo et al., 2000). As such, the clear differences that have been found between these types of masking and crowding may not be so apparent with OSM.

In fact, when examining the mechanisms underlying crowding and OSM, it becomes clear that they share some similarities, at least superficially. As discussed in section 3.1.1 one of the hallmarks of crowding is that it scales with eccentricity. In common with this there is evidence that the magnitude of OSM increases with increased display eccentricity (Di Lollo et al., 2000; Jiang & Chun, 2001; Lleras & Moore, 2003). There is also evidence of an inward-outward anisotropy in OSM as is found in crowding. That is, stronger masking is produced with masks that appear more eccentrically than the target than with those presented towards fixation (Jiang & Chun, 2001; Lleras & Moore, 2003; Moore & Lleras, 2005). Additionally, there is some suggestion that like crowding, OSM tends to be strong where the task requires the conjunctive binding of features (Bouvier & Treisman, 2010; Koivisto & Silvanto, 2011).

Furthermore, crowding and OSM have both been found to be sensitive to the visual similarity between the target and flankers. Crowding and OSM are both attenuated when the target is distinguishably different in the display. For instance, crowding is diminished or even abolished when a target differs in shape, colour, or orientation from the crowding-producing flankers (Bernard & Chung, 2011; Chung et al., 2001; Hariharan, Levi & Klein, 2005; Kooi, Toet, Tripathy, & Levi, 1994). Like crowding, OSM can be largely attenuated when the target is distinctive in the display. For example, when the target is distinguishably different from the other display items in its colour or orientation, OSM has been found to be greatly reduced or even absent (Di Lollo et al., 2000; Gellatly et al. 2006; Lleras & Moore, 2003; Moore & Lleras, 2005; Tata, 2002). Of course it is possible that these similarities between OSM and crowding are only superficial in nature and merely coincidental. However they may alternatively indicate some common underlying process or processing bottleneck from which the two phenomena emerge.

3.1.6 Interactions between crowding and masking

As was shown in section 3.1.5, the phenomena of OSM and crowding appear to be at least to some extent similar in nature. Consequently, this may mean that they share some common mechanisms. If this is the case, OSM and crowding should be found to interact when the two phenomena are combined within the same psychophysical paradigm. Indeed the interaction between crowding and masking (both generally and in one case specifically with OSM) has been investigated in a small number of studies. This has included observing how crowding is affected by SOA variations (Huckauf & Heller, 2004) and the effect of masking surrounding flankers using OSM, noise and pattern masks (Chakravarthi & Cavanagh, 2009). The interaction has also been investigated by determining how crowding is impacted when a crowded target is also masked by a surround mask (Vickery et al., 2009). Each of these three studies of the crowding×masking interactions will now be discussed in turn.

One of the first examinations of the relationship between crowding and masking came from Huckauf and Heller (2004). They examined the effect of SOA – a common manipulation in interruption and metacontrast masking studies as well as some OSM studies - on crowding. The target and two flankers were presented for 50ms. Importantly however, the flankers were presented either at the same time as the target (simultaneous onset) or up to 150ms (50, 100 or 150ms) before or after the target. The target-flanker distance was also manipulated (as is typical in crowding). In this experiment the surrounding flankers were also classified as masks when the target-flanker onset was asynchronous. With the simultaneous onset condition, Huckauf and Heller (2004) found a typical crowding effect. That is, crowding decreased as target-flanker distance increased.

When the target and flankers onset asynchronously however an interesting pattern of results was revealed. At the small target-flanker distance, the effect of SOA produced a monotonic decline in performance (as measured by a letter identification task) with increased SOA. With increased target-flanker distance however a non-monotonic decline in performance was produced. That is, at the larger target-flanker distances the greatest performance impairment occurred at a 50ms SOA. This means that there was possibly an additive effect of masking when the flankers onset 50ms after the target. Thus, the distance with which crowding of the target occurred was increased with the 50ms SOA. These results indicate therefore than the additional masking caused a transition between a Type A and Type B masking function when the flankers did not closely crowd the target. Thus in this case crowding determined the nature and characteristic pattern of the masking observed.

Masking of the target has also been shown to increase the critical distance with which crowding is observed for a simultaneously presented surround mask. Vickery et al (2009) examined the impact of a weak surround mask on crowding. They presented a standard crowding paradigm in which a target (a 'T' in one of four orientations) was surrounded by four flanking T's (each in one of four random orientations) at three target-flanker distances. The task was to indicate the orientation of the target T. Target-flanker distances were varied in relation to eccentricity in keeping with Bouma's (1970) law of critical spacing. Four target-flanker distances were given. These distances, as a proportion of the target-display eccentricity, were 0.3, 0.5, 0.7, or infinity (i.e. no flankers present). On half the trials the target was also surrounded by an outline mask which onset and offset with the target. This mask was quite distinct from the target (in one experiment an outline square, in another a random pattern) and it had a different luminance polarity (the target and flankers were black, the mask white). Thus the mask, by itself, was unlikely to produce any crowding of the target given its very different perceptual properties to the target object.

Vickery et al (2009) found that the use of a mask in combination with crowding flankers increased the crowding window substantially beyond the critical spacing window (a proportion of 0.5 of target eccentricity) that has been so robustly observed previously and enshrined in Bouma's (1970) law (Levi, 2008). On trials in which the mask was absent Vickery et al (2009) obtained a typical crowding function as target-flanker distance was varied. That is, substantial crowding was produced at the 0.3 distance with little crowding produced beyond this point (performance with crowders of 0.5 or 0.7 was not significantly different to the infinity condition in which no crowders were present). The mask by itself had very little effect on performance. This could be seen in the fact that in the absence of flankers (target-flanker distance="infinity") masking had only a mild effect on performance.

What was interesting was, despite the seeming ineffectual nature of the mask under uncrowded conditions, with flankers the masking function was clearly different. Specifically an extended crowding function was obtained. That is, crowding was still evident even with flankers at a distance of 0.7 of the target eccentricity where unlike for unmasked trials, performance remained far lower than at infinity (see Figure 13). Thus it seems that masking strongly interacted with crowding in a way which extended its spatial window beyond that normally observed for uncrowded targets and beyond what is predicted by Bouma's law (1970).

Vickery and colleagues (2009) labelled this effect of masking on crowding as "*supercrowding*". Further experiments showed that this supercrowding persisted across mask types and presented with many of the typical characteristics associated with crowding. For instance "supercrowding", as with crowding, was strongly influenced by target-flanker similarity and displayed the signature inward-outward anisotropy found for conventional crowding (Vickery et al, 2009). This suggests that the critical spacing window in crowding is not fixed in the visual system as earlier authors have assumed. Rather it seems crowding is dependent on the perceptibility of the target. Its effects seem to be amplified under conditions in which the target is partially degraded such as through masking.

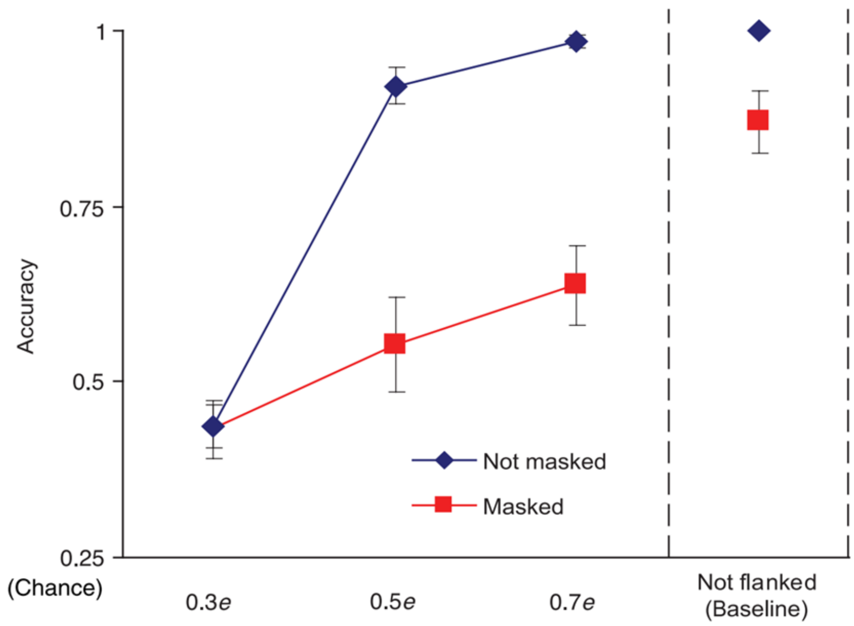

Figure 13| Performance in Experiment 1 of the Vickery and colleagues (2009) paper (taken from Vickery et al., 2009, Figure 3, page 5). The figure shows accuracy (% correct) at the three target-flanker distances (0.3, 0.5 and 0.7 of the target eccentricity). Error bars represent +/- 1 standard error of the mean.

Chakravarthi and Cavanagh (2009) investigated the question of the relationship between crowding and masking in a rather different way. Rather than looking at the consequences of masking the target in a crowding paradigm as Huckauf and Heller (2004) and Vickery et al (2009) had done, these authors instead looked at the consequences for crowding when masking the flankers themselves. Chakravarthi and Cavanagh investigated the effect of three different types of backwards mask (pattern, metacontrast, 4DM [OSM]) along with a no-mask baseline.

In their task they presented a target Landolt C in one of four cardinal orientations. This target was surrounded by four flanking Landolt Cs each at one of the four cardinal positions around the target. Each of the flankers was randomly presented in one of four orientations. The task was to report the orientation of the target. Masks were presented at the location of each of the four flankers; the target itself was never masked. The critical variable for this experiment was whether the flankers were masked or unmasked. They found that when a noise or pattern mask was used the crowding effect produced by these (masked) flankers was significantly reduced. In contrast, when the flankers were masked by a four dot (OSM) mask, no release from crowding was observed: crowding was as strong as the baseline condition in which no masks were given.

Chakravarthi and Cavanagh (2009) argued that noise and pattern masks abolished the crowding effect because these forms of masking impair stimulus processing early in the visual stream. They argued this interruption of processing occurs at a stage in the visual hierarchy before crowding occurs. In contrast, OSM was argued to have no influence on the crowding effect because this form of masking occurs later in the processing hierarchy. Chakravarthi and Cavanagh argued that this dissociation between forms of masking to reduce crowding indicates that crowding must occur at a stage later than that of pattern and noise masking but at an earlier stage than that of OSM. Breitmeyer (2014) reiterated this claim regarding the late stage nature of OSM. He presented a formal model of the visual processing hierarchy in which OSM was at the latest stage of object processing (see Figure 14).

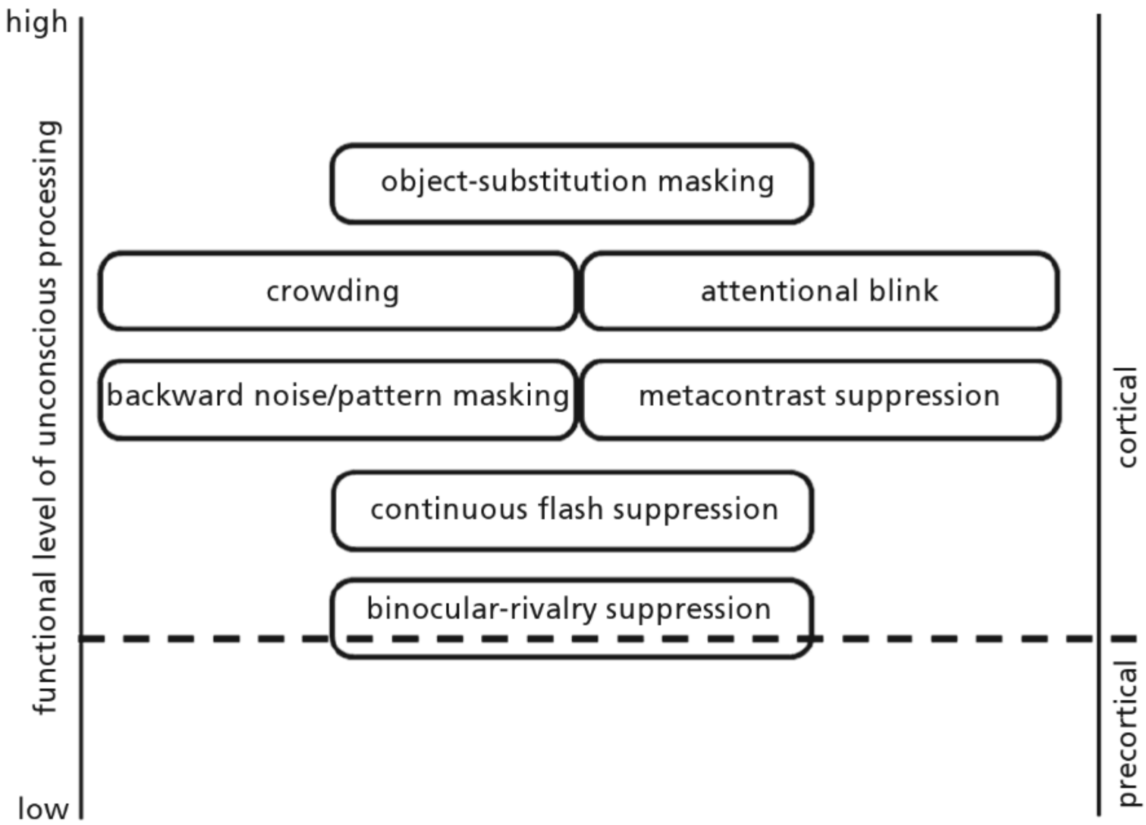

Figure 14| A diagrammatic representation of the proposed object processing hierarchy (taken from Breitmeyer, 2014; Figure 5.4, page 101).

3.1.7 Summary

Crowding, like masking, is a visual phenomenon that results in a failure in visual awareness of a target (Breitmeyer, 2014; Breitmeyer, 2015; Huckauf & Heller, 2004; Pelli et al., 2004). Nevertheless, it can be reasonably claimed that crowding and masking are distinct phenomena, each with distinct, well established and reliable characteristics (Huckauf & Heller, 2004; Pelli et al., 2004). Despite this, OSM and crowding appear to share a number of characteristics, at least superficially (Bernard & Chung, 2011; Chung et al., 2001; Di Lollo et al., 2000; Levi, 2008; Lleras & Moore, 2003). There is also evidence that masking and crowding can interact at some level within the visual processing stream (Chakravarthi &

Cavanagh, 2009; Huckauf & Heller, 2004; Vickery et al., 2009). However, there is some suggestion that OSM may be distinct from classical forms of masking such as pattern and metacontrast in this respect: OSM is unable to prevent crowding from occurring when used to mask flankers. This evidence has been used to claim that OSM occurs later in the visual processing stream than classical forms of masking (Breitmeyer, 2014; Breitmeyer, 2015; Chakravarthi & Cavanagh, 2009; see also Enns, 2004 for further evidence of the seeming late-stage nature of OSM).

3.1.8 Aims of experiments 6-10

It has been shown that there are a number of apparent similarities between OSM and crowding in terms of some of their basic signature characteristics. There are also similarities in terms of the fact that they impede conscious perception of the target. Furthermore, recent evidence has found that masking and crowding phenomena interact under some circumstances to modulate either effect.

Given these factors, it seems reasonable to question whether crowding could be a factor in OSM and may explain something about the role of distractors in the phenomenon. That is, it seems worth questioning whether the set size effects found in Chapter 2 are truly set size effects or if they are a consequence of the fact that the extent to which the target was flanked increased with set size. If this is the case it would be expected that as set size increases and correspondingly the distance between target and the nearest distractors is reduced, the target would become increasingly crowded.

As was stated previously, the design of the experiments in Chapter 2 meant that distractor proximity always co-varied with set size. That is, with a set size of 1 there were no distractors, with a set size of 6 or 12 the target was increasingly flanked by distractors. This is not unique to the experiments in Chapter 2, it is also the case in all of the published OSM experiments to date that have investigated set size (see section 1.6.1). Thus it is possible that crowding, not the number of items per se, was driving the interaction found between set size and OSM in Chapter 2. In order to test this it is necessary to experimentally attempt to decouple the two factors from one another.

The experiments in this chapter therefore aimed to explore if the proposed set size effect in OSM is in fact because of set size or if rather it is a consequence of crowding with increased set sizes. These experiments started by investigating the role of set size and crowding in OSM independently of one another in an attempt to resolve which of these factors does in fact drive the observed interaction with masking.

To pre-empt the results of this chapter, five experiments were carried out investigating crowding in OSM. These experiments initially found that crowding, rather than set size does indeed interact with OSM. From this point, crowding was systematically examined by varying the distance at which the distractors surrounded the target. These experiments found that not only did the effect of crowding on OSM extend far beyond the distance expected but that this effect also produced a non-monotonic, inverted U-shaped function. That is, the effect of OSM was most prominent not at target-flanker distances that closely surrounded the target but rather at medium target-flanker distances that extended beyond the expected critical spacing window (Bouma, 1970). It is worth noting at this point that the terms “distractors” and “flankers” will be used interchangeably to refer to the same stimuli from this point.

3.1 Experiment 6: Establishing the presence of crowding effects in the OSM paradigm

Experiment 6 used the same stimuli (digits) and task (digit identification) as Experiment 1. Experiment 6 was conducted to first establish if crowding effects could be achieved regardless of OSM with the type of stimulus display used in this series up to this point. Specifically, Experiment 6 aimed to investigate whether crowding effects would occur when distractors flanked the locations adjacent to the target under the sorts of stimulus conditions (circular arrays, target denominated by four surrounding dots; digit stimuli, identification task) that were given in some of the key experiments in the last chapter. It was predicted that strong crowding would occur when distractors were presented close to the target whereas little to no masking would occur when distractors were presented opposite the target.

Method

Participants

Ten participants (8 female) took part in the experiment. These were recruited from staff and students at Oxford Brookes University. All participants reported normal or corrected-to-normal visual acuity.

Stimuli and procedure

The stimulus array consisted of four digits: a target and three distractors. These were positioned on a virtual circle of the same dimensions as Experiment 1 (3.9°). Viewing conditions were also the same as Experiment 1 (see section 2.2). The target (identified by the surrounding four dots) was presented at a random position on the virtual circle always with one distractor directly opposite it. This basic arrangement was presented under crowded and uncrowded conditions. On crowded trials the two distractors flanked the target on either side (target and distractors were separated by a circumferential distance of 1.22° visual angle between the centres of the respective stimuli; see Figure 15 where the “5” and “3” flank the “7”). On uncrowded trials it was the distractor opposite the target which was flanked by the two distractors and those positions adjacent to the target were left empty (see Figure 15 where the “4” is flanked by the “3” and “7”).

This arrangement ensured that there was always symmetry across crowded and uncrowded trials in the stimulus array. Consequently, the distribution of spatial attention across the display items was likely to be comparable across the two condition types. Participants had to report the identity of the digit surrounded by the four dots in an unspeeded manner. Unlike previous experiments mask duration was not varied: the four dots always offset with the stimulus array. A demonstration and 30 practice trials were given before commencing the experiment. The experiment consisted of 120 uncrowded and 120 crowded trials.

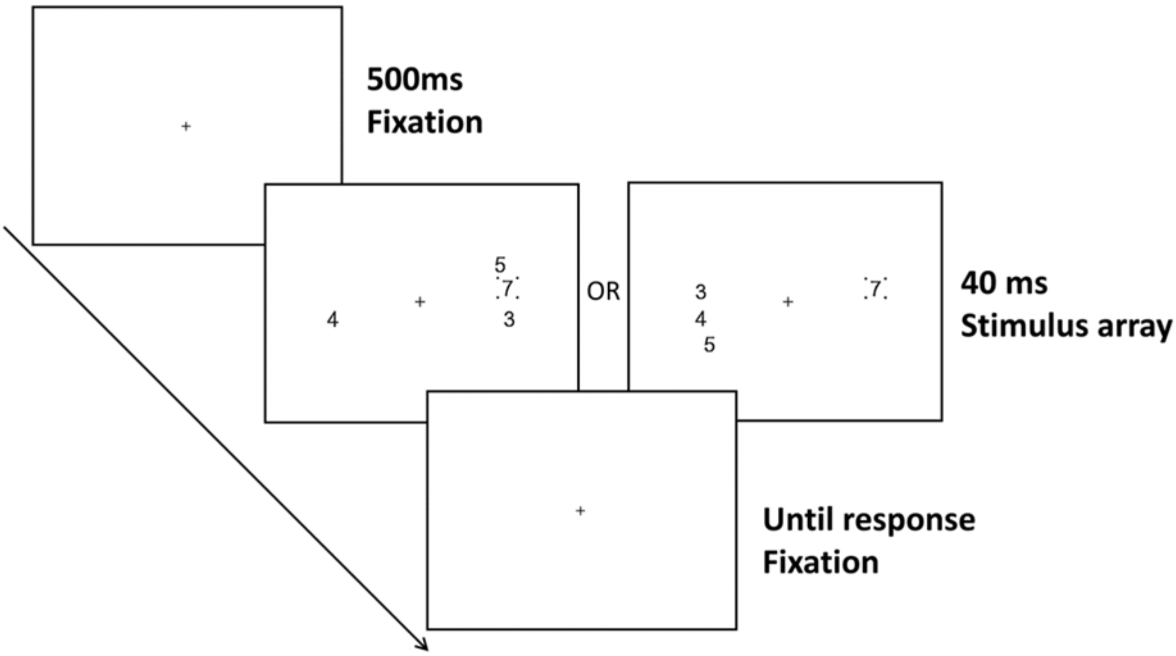

Figure 15| A schematic depiction of the trial sequence in Experiment 6 (Establishing the presence of crowding effects in the OSM paradigm). The left display shows a crowded trial (“7” as target); the right display shows an uncrowded trial (“7” as target).

Results and Discussion

The mean percent correct performance for the uncrowded and crowded conditions is shown in Figure 16(A). For reasons of consistency with the other experiments the mean of the log transformed scores is also presented (Figure 16[B]). As can be seen, when the target was closely flanked by distractors performance was substantially lower than when the distractor directly opposite the target was flanked, $t(9)=4.90$, $p=.001$. This fact demonstrates, as was suspected, that distractors produce crowding when located near the target under the conditions of these stimulus displays. Having established that crowding does occur under these conditions, Experiment 7 introduced a series of conditions in which crowding and set size were independently manipulated under both masked and unmasked conditions.

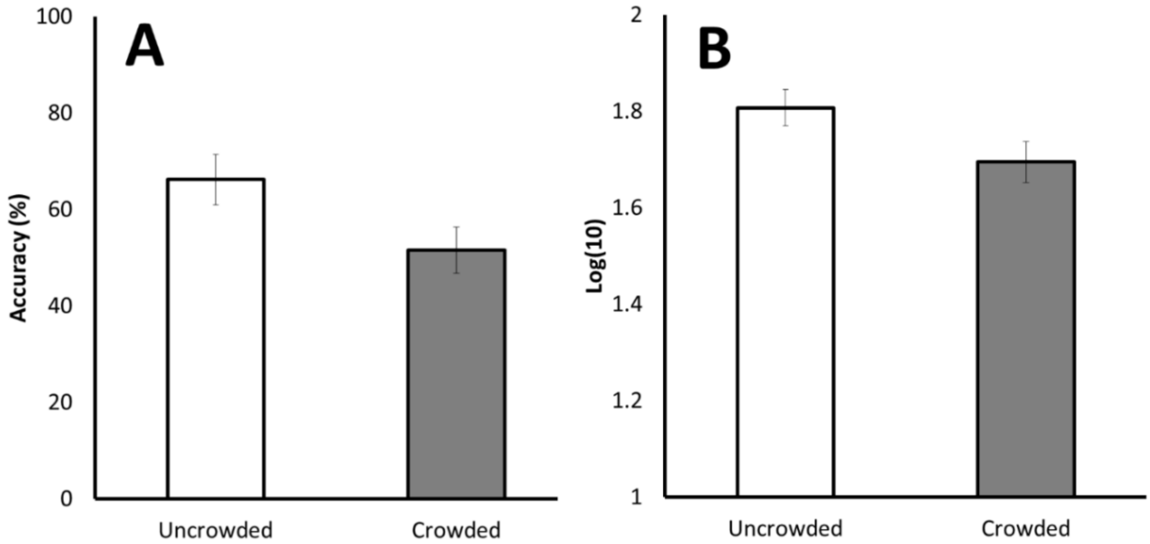

Figure 16| Performance in Experiment 6 (uncrowded vs. crowded). This is shown as the mean percentage correct scores (plate A) and as the mean Log10 transformed scores (plate B). Error bars represent +/-1 standard error of the mean.

3.2 Experiment 7: Assessing the effect of crowding and set size on OSM

Experiment 7 followed the basic paradigm of Experiment 6. Unlike Experiment 6 the number of items in the display was varied, as was mask duration. There was always a minimum of four items in the stimulus array (one target, three distractors, as in Experiment 6). However on some trials there were an additional four (set size 8) or eight (set size 12) distractors pseudorandomly positioned at empty locations on the virtual circle of the stimulus array. These additional flankers were positioned with the constraint that they were never presented in positions which crowded either the target or the distractor opposite the target. The presentation sequence of the stimulus arrays was in exactly the same manner as Experiment 6 except that on some trials an additional frame was given after the offset of the target in which the mask trailed the target location.

If set size is itself the relevant factor then an interaction should be found between set size and mask duration as in the previous chapter. However, if distractor proximity with respect to the target is the relevant variable in the previous experiments then an interaction should be found between this factor and mask duration. It was recognised that the two predictions were not necessarily mutually exclusive and both two way interactions in principle could be significant. This would indicate that both set size and crowding independently influence OSM. Indeed the effects of the two variables could be multiplicative. If this was the case then a three-way interaction should be found between all three factors in the experiment. Nevertheless, it was predicted that both set size and crowding would have an effect on overall perceptibility of the target. However, it was predicted that only crowding would affect OSM. That is, only crowding, and not set size, was expected to increase the magnitude of OSM.

Method

Participants

Thirty participants recruited from the Oxford Brookes Participant Panel (19 female) took part in the experiment. All gave informed consent. Participants received either £7 remuneration or course credits for completing the experiment. All participants reported normal or corrected-to-normal visual acuity.

Design

The experiment had three within-subjects variables. These were *set size* with three levels (4, 8, or 12 items), *mask duration* with two levels (0, 180ms), and *crowding* with two levels (crowded, uncrowded).

Stimuli and procedure

The stimulus array consisted of a target and three, seven or eleven distractors positioned on a virtual circle depending on the trial type. On all trials the target was presented at a random position on the virtual circle with one distractor directly opposite. On crowded trials the target was flanked on either side (a circumferential distance of 1.22°). This target-flanker distance was within the expected crowding window (with the critical window of this display at 1.95˚). On crowded trials the locations adjacent to this distractor were always empty (see Figure 17 where the target digit “7” is flanked by the digits “5” and “3” in all set size conditions); on uncrowded trials the distractor opposite the target was itself flanked by two distractors and the positions adjacent to the target were empty (see Figure 17 where the target is the digit “4” located opposite the above mentioned digit "7 in all set size conditions).

With a set size of 8 or 12 items, the additional 4 or 8 flankers were presented at unoccupied locations on the virtual circle. This placement was done with two constraints. Firstly there was always a minimum circumferential distance of 1.22° between each additional distractor on the virtual circle. Secondly, on uncrowded trials, there was a minimum circumferential distance of 3.66° between the additional flankers and the target; on crowded trials there was always a minimum circumferential distance of 3.66° between the additional flankers and the distractor positioned opposite the target. Due to the added crowding conditions the number of mask duration conditions was reduced to two: 0ms (simultaneous mask offset) and 180ms (delayed mask offset). There were 600 randomly ordered trials, 50 for each of the twelve factorially combined conditions of *crowding*, *set size* and *mask duration*. The experiment was conducted in 10 blocks and the computer prompted the participant to take a brief break after each 60 trial increment. A demonstration and practice trials were given, as previously described.

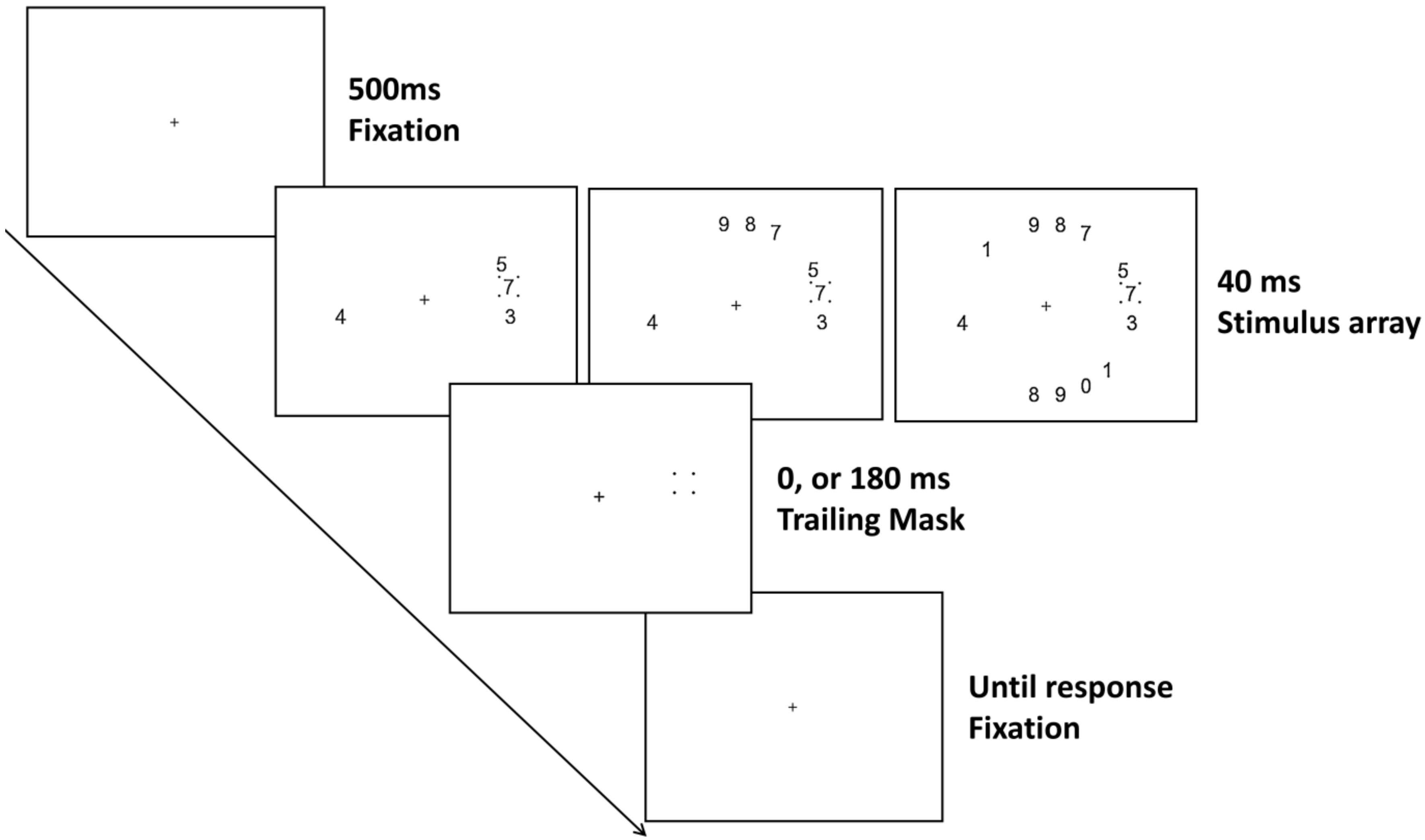

Figure 17| A schematic depiction of the trial sequence in Experiment 7 (set size vs. crowding). The three stimulus array frames depict examples of trials for (from left to right) set size 4, 8, and 12.

Results

One participant had to be excluded from the analysis as their overall performance was at chance level (13%). Mean percent correct data for each combination of set size and mask duration were examined and are shown in Figure 18.

A 3-way repeated measures ANOVA was conducted on the data from the remaining participants. This revealed a significant main effect of all three factors: *crowding* ($F[1, 28]=176.61$, $MS^{error}=106.72$, $p<.001$, $\eta_p^2=.86$), *mask duration* ($F[1, 28]=91.90$, $MS^{error}=89.56$, $p<.001$, $\eta_p^2=.77$), and *set size* ($F[2, 6]=18.03$, $MS^{error}=30.98$, $p<.001$, $\eta_p^2=.39$). Thus, crowding, set size and mask duration all independently influenced target perceptibility. The interaction between *crowding* and *mask duration* was significant, $F[1, 28]=5.70$, $MS^{error}=41.46$, $p=.024$, $\eta_p^2=.17$. The interaction between *set size* and *mask duration* was non-significant, $F[2, 56]=.59$, $MS^{error}=36.07$, $p=.592$, as was that between *crowding* and *set size*, $F[2, 56]=0.53$, $MS^{error}=35.49$, $p=.591$. The 3 way interaction (*set size*×*crowding*×*mask duration*) was also non-significant ($F[2, 56]=.50$, $MS^{error}=29.22$, $p=.610$).

With the log transformed data the *crowding*×*mask duration* interaction was even more pronounced ($F[1, 28]=9.26$, $MS_{error}<.01$, $p=.005$, $\eta_p^2=.25$), while the *set size*×*mask duration* interaction remained non-significant; $F[2, 56]=.50$, $MS^{error}<0.01$, $p=.607$. As with the untransformed scores none of the other interaction terms approached significance. Figure 15 shows that the significant crowding×mask duration interaction reflects the fact that OSM was stronger when the target was crowded by flankers compared to when it was not.

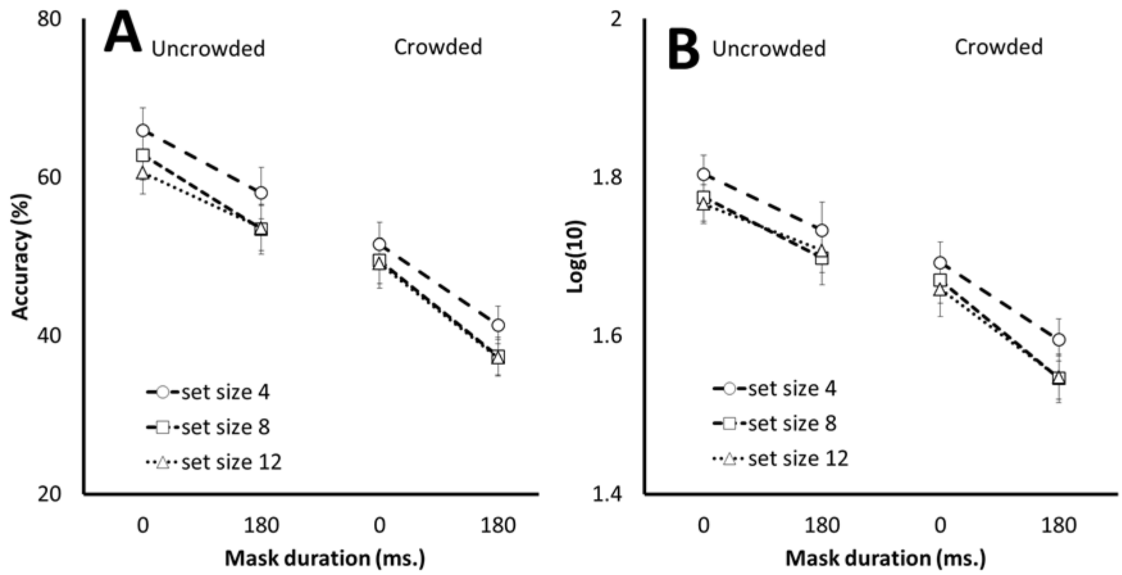

Figure 18| Performance in Experiment 7 (Set size vs. crowding). Uncrowded trials are shown on the left half of the graph, crowded trials are shown on the right half. The figure shows accuracy (% correct; plate A) and transformed accuracy (Log10; plate B) for the three set size conditions (4,8,12) by each of the two mask duration conditions (0, 180ms). Error bars represent +/-1 standard error of the mean.

Discussion

Experiment 7 showed that set size in itself had no significant effect on OSM. Masking by OSM – as indexed by mask duration – was of similar magnitude irrespective of whether there were four, eight, or twelve display items. At the same time it is notable that set size did affect overall task performance. Accuracy declined significantly with the number of distractors present. In contrast, the crowding manipulation, as well as influencing overall performance also had a specific influence on OSM. Performance was most affected by crowding under conditions where the target had a trailing mask. This suggests that the OSM effect was augmented by the crowding effect produced by the closely surrounding flankers compared to when the target adjacent locations were empty.

Thus, Experiment 7 suggests that the ostensible set size effects found for OSM that were reported in Chapter 2 (Experiment 1-5) had nothing to do with set size itself (i.e. the number of distractor items present in the display). Rather, these effects appear to be a consequence of the proximity of flankers to the target, increasing proportionally as set size itself was increased.

It could perhaps be argued that the failure to find an interaction between set size and mask duration in Experiment 7 is a reflection of the fact that set size was not varied to the same extent that it was in the five experiments in Chapter 2. In these Experiments set size was always varied between a minimum of 1 item (target alone) and a maximum of 12 items (target+11 distractors). In Experiment 7 however set size was only varied between a minimum of 4 and a maximum 12 items. This larger minimum set size condition is a necessary consequence of having to vary crowding independently of set size (since it is logically not possible to have crowding without the presence of flankers and, as was mentioned earlier, in order to balance attention across the display it is necessary to have a design in which a distractor is always opposite to the target).

Could this restricted set size range possibly explain the failure to observe an interaction between set size and mask duration? The data give no indication that this is the case: Though the set size variable was more restricted in range it still showed a substantive main effect on performance which was highly significant. This suggests that even with this curtailed range there was still ample opportunity for an interaction with mask duration to have revealed itself if it existed. Consequently, the evidence from Experiment 7 seems to show that set size does not interact with mask duration when this factor is isolated from crowding. The possibility that set size could interact with mask duration where a larger set size range is given cannot be ruled out entirely. It would be difficult to design an experiment to test this with the current stimuli. To have the same set size range as in Chapter 2 would require set size to be varied between 4 and 15 items. It would be difficult, if not impossible to have a

15 item display in which crowding of the target could be independently manipulated, at least with the current stimuli. In any case the data presented here give no reason to suspect that set size effects would reveal themselves under these circumstances.

3.3 Experiment 8: Flanker distance and the crowding×OSM interaction

Experiment 8 was conducted to explore the nature of the crowding×OSM interaction. This experiment aimed to understand how robust and wide ranging it is. This was done under conditions where set size was removed entirely as a factor. As such, a further concern of this experiment was to establish if these crowding effects could be replicated without the set size variation. It was expected that this interaction between crowding and OSM would represent OSM being greatest at the smallest target-flanker distance (where crowding is greatest) and monotonically declining with increased target-flanker distance.

Because of the absence of any effect of set size on OSM as revealed in Experiment 7, this and all further experiments in this thesis did not have set size as a manipulated variable. There were always three flankers presented with the target on any given trial. Of interest in this experiment was the spatial character of the effect of the flankers on OSM. That is, whether the effect of the flankers on masking showed a monotonic decline with distance consistent with the decline that is seen for crowding effects generally. The target-flanker distance was systematically varied between 0.63˚ and 1.41˚ under conditions of a simultaneous and trailing mask duration.

Method

Participants

Thirty-five first year Oxford Brookes Psychology students (27 female) took part in the experiment. All participants gave informed consent and received course credits for completing the experiment. All participants reported normal or corrected-to-normal visual acuity.

Stimuli and procedure

Stimuli and procedure were identical to those used in Experiment 7 (see section 3.3). However in this experiment set size was kept constant at 4 items. On each trial the target was presented in either a crowded (with 2 distractors flanking the target; see Figure 19 where the "7" is the target) or an uncrowded (with no distractors flanking the target; see Figure 19 where the "6" would be the target) location on the screen as with Experiment 7. The target-flanker distance was varied over four conditions. The four conditions of target-flanker distance (in terms of degrees of visual angle) were 0.63°; 0.89°; 1.15° and 1.41°. Expressed as a proportion of the target eccentricity these target-flanker distances are, respectively, 0.2, 0.23, 0.3 and 0.4. Participants were required to report the identity of the target digit. The experiment was a within-participants design with three factors: *crowding* with two levels (crowded vs. uncrowded), *mask duration* with two levels (0ms vs. 180ms) and *target-flanker distance* (distractor-distractor distance on uncrowded trials) with four levels (0.63°; 0.89°; 1.15°; 1.41°). The dependent variable was *identification performance*; measured by the percentage of correct responses.

There were 640 randomly ordered trials, 40 trials for each combination of *crowding*, *mask duration* and *target-flanker distance*, presented in 10 distinct blocks. The computer prompted the participant to take a brief break after each 64 trial increment. A demonstration and practice trials were given as in the previous experiments. Participants were instructed to emphasise accuracy rather than speed in responding. The total experimental session lasted approximately 30 minutes.

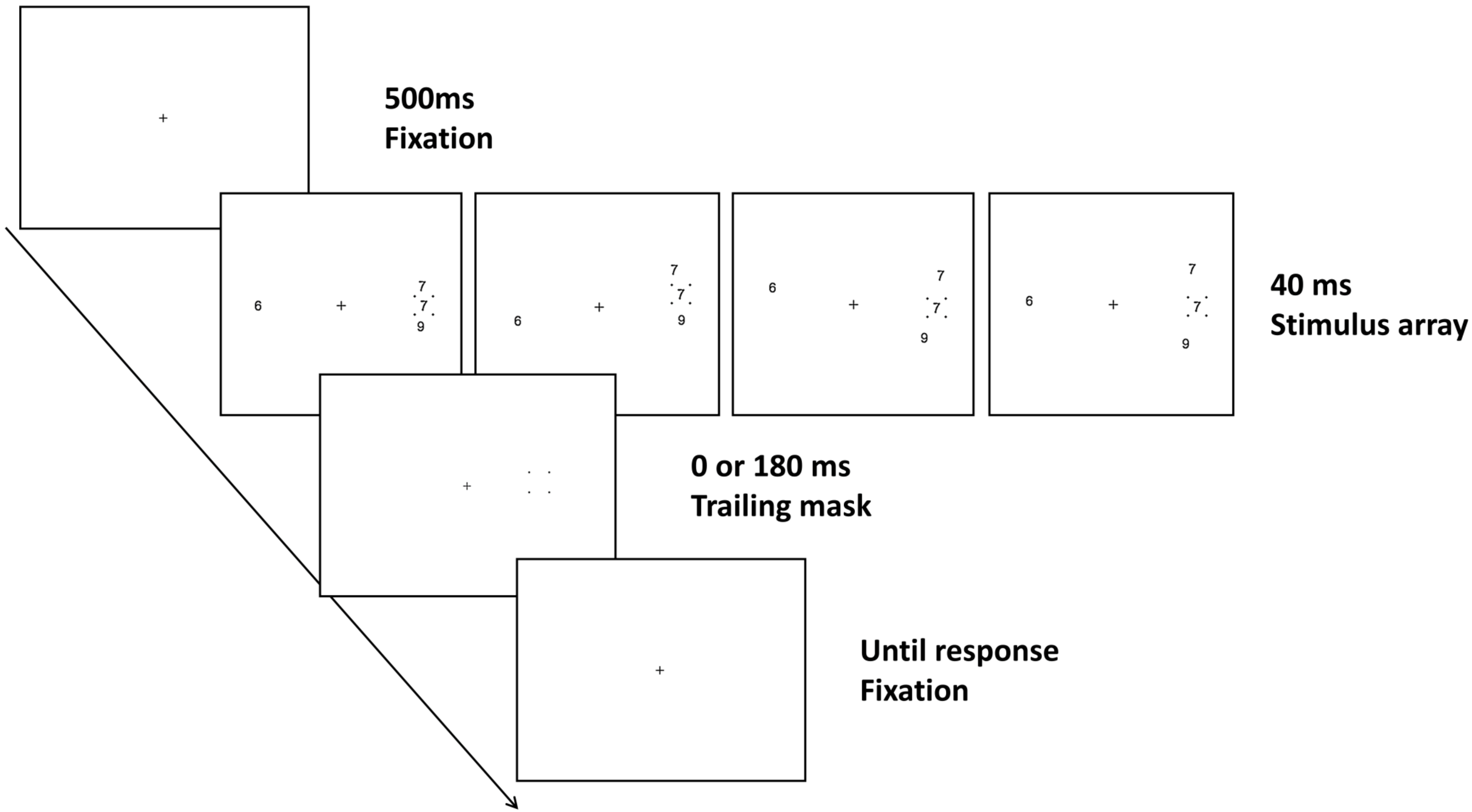

Figure 19| A schematic depiction of the trial sequence in Experiment 8 (crowding distance). The four stimulus array frames depict examples of trials for (from left to right) a target-flanker distance of 0.63°, 0.89°, 1.15° and 1.41° for the crowded condition. In uncrowded trials the distractor opposite the target would be flanked instead of the target at each of the four distances presented here.

Results

The average percent correct responses in each factorial condition of crowding, mask duration, and target-flanker distance are shown in Figure 20(A). In this figure it can be seen that there is a clear decline in the amount of crowding produced in the unmasked condition. This indicates that the target-flanker manipulation was sufficient to produce a noticeable reduction in crowding as flankers were moved away from the target. This can be seen when looking at the uncrowded and crowded 0ms mask conditions for the different target-flanker distances where the lines start to converge with increased target-flanker distance. However, the performance in these conditions never meets entirely. This suggests that even at the largest target-flanker distance there is still some crowding.

This is also shown in the statistical data. That is, when the data were analysed without masking as a factor there were substantial effects of *crowding* and *target-flanker distance*. Specifically, there was a significant effect of crowding and of target-flanker distance ($F[1, 34]=117.48$, $MS^{error}=137.05$, $p<.001$, $\eta_p^2=.78$ and $F[3, 102]=6.03$, $MS^{error}=47.06$, $p=.001$, $\eta_p^2=.15$ respectively). These findings indicate that performance was worse when the target was surrounded by distractors compared to when the distractors were positioned opposite the target. Furthermore, it was shown that the impairment caused by crowding reduced as the distance between the target and surrounding distractors increased.

These data were further analysed using a repeated measures ANOVA with three factors: *crowding* (uncrowded; crowded); *mask duration* (0; 180); and *target-flanker distance* (0.63°; 0.89°; 1.15°; 1.41°). Significant main effects were found for *crowding*: $F(1, 34)=174.56$, $MS^{error}=220.14$, $p<.001$, $\eta_p^2=.84$, *masking*: $F(1, 34)=212.77$, $MS^{error}=50.15$, $p<.001$, $\eta_p^2=.86$ and *target-flanker distance*: $F(3, 102)=7.08$, $MS^{error}= 44.46$, $p<.001$, $\eta_p^2=.17$ with reduced performance when the target was crowded, when the mask persisted and with increased target-flanker proximity (in the crowded condition, distractor-distractor proximity in the uncrowded condition), as predicted. Importantly, and replicating the findings of the previous experiment, a significant interaction between *crowding* and *masking* was observed: $F(1, 34)=5.44$, $MS_{error}=50.54$, $p=.026$, $\eta_p^2=.14$. A significant interaction was also produced between *crowding* and *target-flanker distance*: $F(3, 102)=11.72$, $MS_{error}=47.26$, $p<.001$, $\eta_p^2=.26$. However, no interaction was found between *mask* duration and *target-flanker* distance: $F(3, 102)=1.47$, $MS_{error}=40.63$, $p=.226$. With the log transformed data the *crowding*×*mask duration* interaction was even more pronounced ($F[1, 34]=34.15$, $MS_{error}<0.01$, $p<.001$, $\eta_p^2=.42$). These findings suggest that OSM is indeed amplified by crowding of the target. That is, the effect of OSM becomes more prominent when the target is closely flanked by distractors.

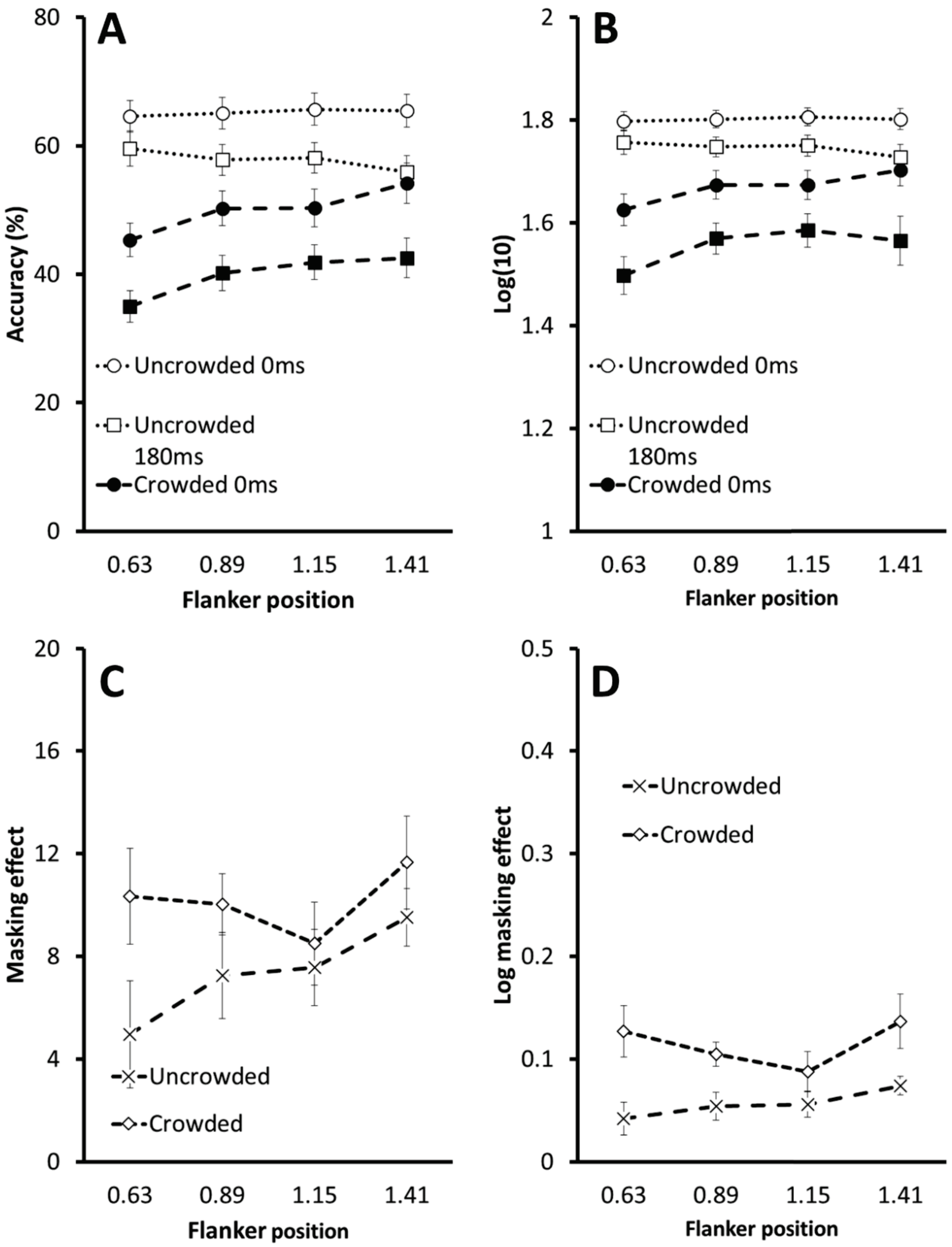

Figure 20| Performance in Experiment 8 (crowding distance). The figure shows accuracy (% correct; plate A) and transformed accuracy (Log10; plate B) for the four target-flanker distances (0.63°, 0.89°, 1.15°, 1.41°) by each of the two mask duration conditions (0, 180ms). Plate C shows the masking effect (difference between 0ms and 180ms mask duration) for the accuracy data and Plate D shows the masking effect for the transformed accuracy data across the four target-flanker distances. Error bars represent +/-1 standard error of the mean.

Discussion

This study provides clear evidence of an effect of crowding on OSM in the absence of set size. The findings of Experiment 8 show that crowding had a significant impairment on performance irrespective of masking. This can be seen in Figure 20(A) when looking at the crowded and uncrowded conditions for unmasked trials where performance was substantially lower under crowded conditions. Furthermore, the target-flanker distances used in Experiment 8 showed a significant reduction in crowding as the distance increased. This can be seen in Figure 20(A) when looking at the unmasked trials where performance was lowest at the smallest target-flanker distance and increased with increased target-flanker distance under crowded conditions. Moreover, the results of Experiment 8 showed that OSM significantly increased when the target was crowded.

What was unexpected however was that there was no corresponding decline in the effect of crowding on masking with increased target-flanker distance. A substantial effect of crowding on masking was still evident at the largest target-flanker distance (1.41°). This can be seen in the fact that the relative difference in performance between unmasked and masked trials was still substantially greater for crowded compared to uncrowded trials. Indeed, and contrary to the prediction, if anything the effect of crowding on masking was more evident at this furthest target-flanker distance than it was at the closest distance (0.63˚).

One possibility is that target-flanker distance was not varied over a great enough distance in order to observe the decline in the effect of OSM which presumably must occur with greater target-flanker distances. Thus the effective relationship between OSM and crowding may extend beyond the maximal spatial distance given in this experiment (1.41˚). Indeed on reflection it was clear that the largest target-flanker distance (1.41˚) chosen for Experiment 8 still falls (just) within the expected window for crowding in this display (1.95˚). As such, a further study was warranted that extended the target-flanker distances beyond the point of critical spacing for crowding to determine the spatial character of the crowding effect on OSM in terms of the range in which it operates.

3.4 Experiment 9: Extending target-distractor distance

Experiment 9 was effectively a replication of Experiment 8. However in this experiment the spatial range of target-flanker distances was more widely extended. This increased range included the distances 0.63°, 3.02°, and 4.90° degrees of visual angle for crowded and uncrowded trials. It was anticipated that by substantially extending the size of the distances this would then capture the point at which the crowding effect on OSM diminished. It was expected that OSM would decline with increased spatial distance between the target and distractors (i.e. with increased target-flanker distance).

Method

Participants

Thirty two undergraduate and postgraduate Oxford Brookes Psychology students (27 female) took part in the experiment. All participants gave informed consent and received course credits for completing the experiment. All participants reported normal or corrected-to-normal visual acuity.

Stimuli and procedure

The stimuli and procedure were identical to those of Experiment 8 (see section 3.4) except where stated. To recap, the target-flanker distances in Experiment 8 were 0.63°, 0.89°, 1.15°, and 1.41°. The target-flanker distances in Experiment 9 were changed to 0.63°, 3.02°, and 4.90° degrees of visual angle for crowded and uncrowded trials (see Figure 21 where the "7" is the target). These distances correspond with 0.2, 0.8 and 1.3 times the target eccentricity. There were 480 trials, 30 trials for each combination of crowding, masking and target-flanker distance. The trials were presented within 10 distinct blocks. Participants were asked to take a break after each 48 trial interval.

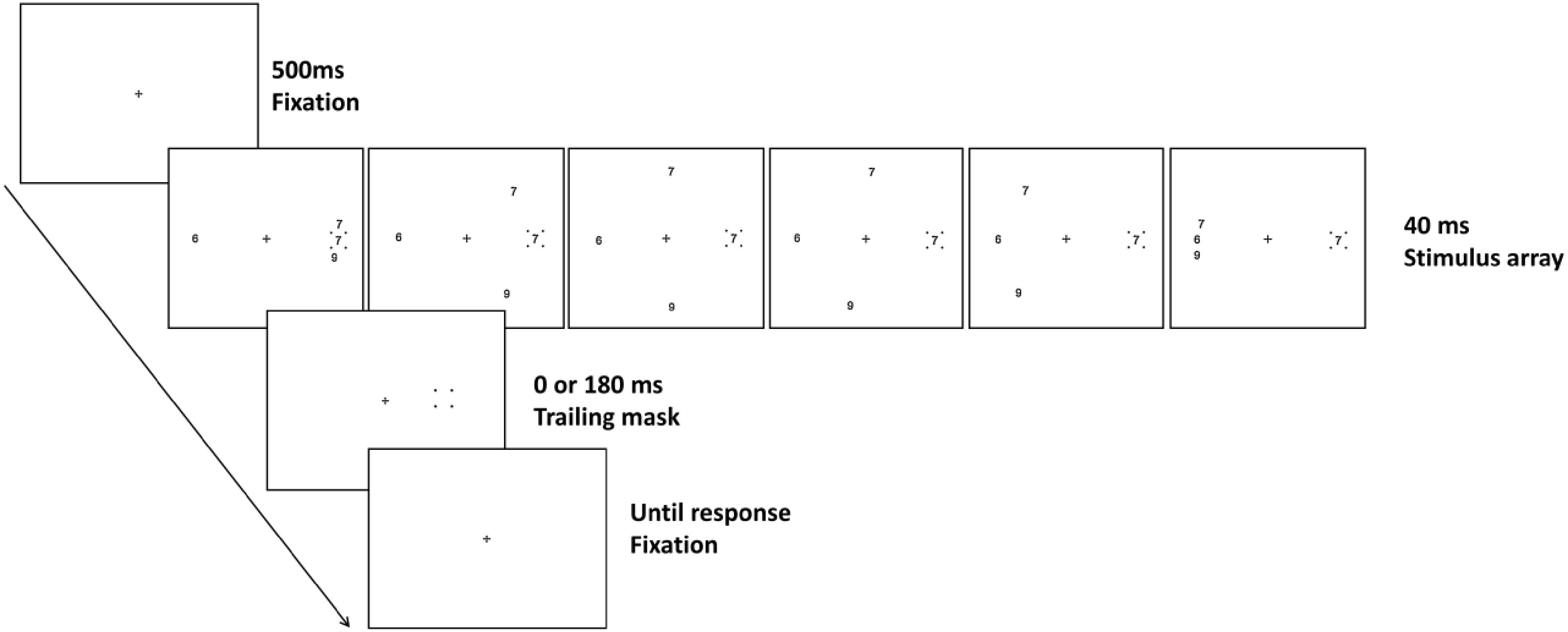

Figure 21| A schematic depiction of the trial sequence in Experiment 9 (extended target-flanker distance range). The six stimulus array frames depict examples of trials for (from left to right) a target-flanker distance of 0.63°, 3.02°, and 4.90° for the crowded and uncrowded conditions.

Results

Figure 22(A) shows the mean percent correct responses selected for each factorial combination of crowding, mask duration and target-flanker distance. These data were initially analysed to look at the effect of crowding irrespective of masking using a repeated measures ANOVA with two factors: *crowding* (uncrowded; crowded) and *target-flanker distance* (0.63°; 3.02°; 4.90°). There was a significant main effect of *crowding* and *target-flanker distance* respectively ($F[1, 31]=55.46$, $MS^{error}=49.02$, $p<.001$, $\eta_p^2=.64$ and $F[2, 62]=53.00$ $MS^{error}=37.49$, $p<.001$, $\eta_p^2=.63$). These findings showed, as with Experiment 8, that distractors that were positioned close to the target produced strong performance impairment whereas distractors that were positioned opposite the target did not. Furthermore, these findings showed that performance increased with increasing target-flanker distance.

Further ANOVA analysis was conducted with three factors: *crowding* (uncrowded; crowded); *mask duration* (0; 180); and *target-flanker distance* (0.63°; 3.02°; 4.90°). Significant main effects were found for *crowding*: $F(1, 31)=138.16$, $MS^{error}=54.52$, $p<.001$, $\eta_p^2=.82$, *masking*: $F(1, 31)=130.53$, $MS^{error}=53.71$, $p<.001$, $\eta_p^2=.81$ and *target-flanker distance*: $F(2, 62)=59.61$, $MS^{error}=39.22$, $p<.001$, $\eta_p^2=.66$. A marginally significant interaction between *crowding* and *masking* was observed: $F(1, 31)=3.49$, $MS^{error}=48.73$, $p=.071$, $\eta_p^2=.10$. A significant interaction was also produced between *crowding* and *distractor distance* $F(2, 62)=108.60$, $MS^{error}=38.13$, $p<.001$, $\eta_p^2=.78$ and *masking* and *distractor distance*, $F(2, 62)=7.80$, $MS^{error}=32.14$, $p=.001$, $\eta_p^2=.20$. There was no significant three-way interaction between *crowding, masking* and *distractor distance*, $F(2, 62)=1.33$, $MS^{error}=51.01$, $p=.271$. With the log transformed data the trend of the *crowding*×*mask duration* interaction did not change ($F[1, 31]=5.73$, $MS^{error}<0.01$, $p=.023$, $\eta_p^2=.42$).

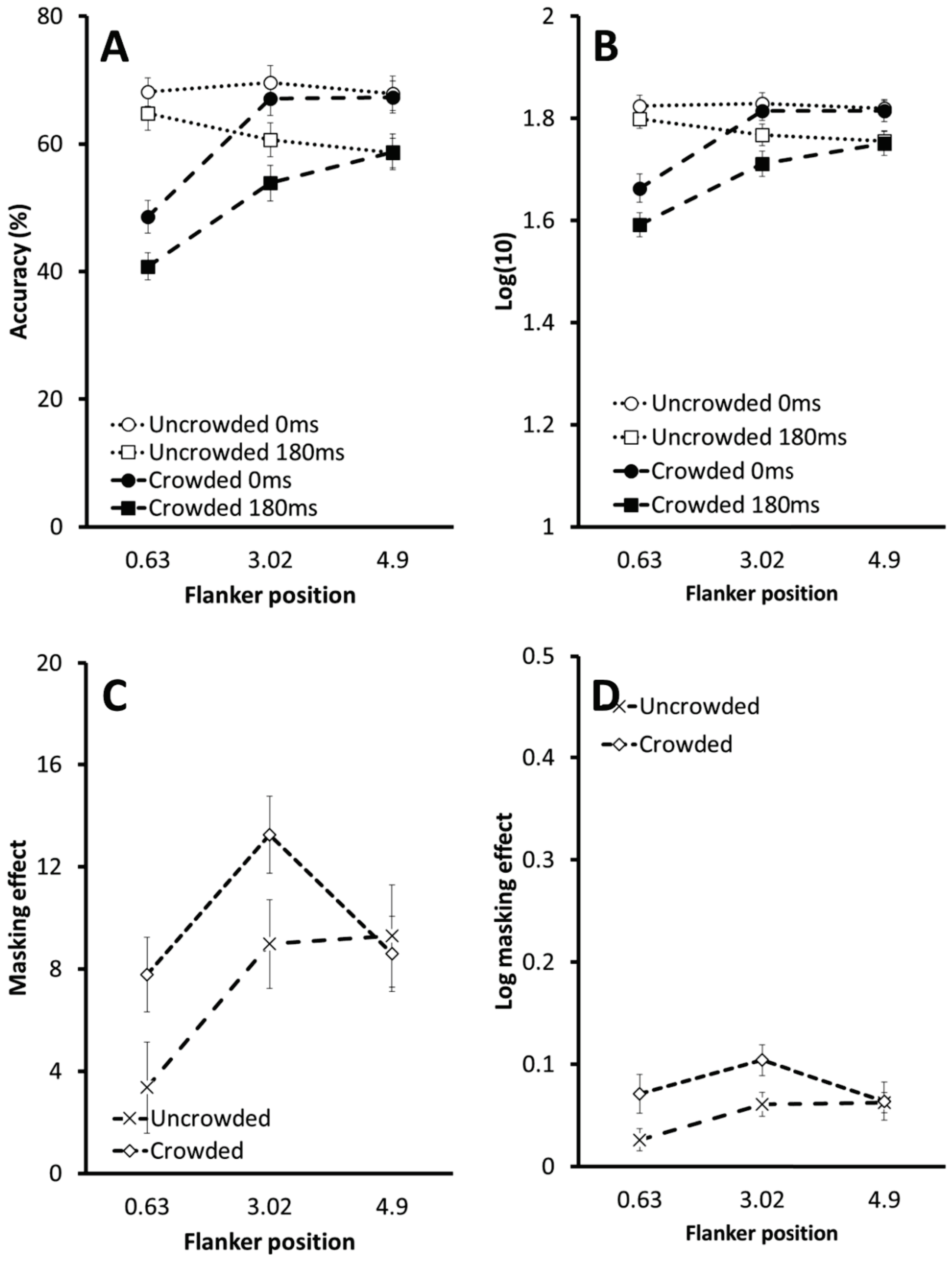

Figure 22| Performance in Experiment 9 (extended crowding distance). The figure shows accuracy (% correct; plate A) and transformed accuracy (Log10; plate B) for the three target-flanker distances (0.63°, 3.02°, 4.90°) by each of the two mask duration conditions (0, 180ms). Plate C shows the masking effect for the accuracy data and plate D shows the masking effect for the transformed accuracy data (difference between 0ms and 180ms mask duration) across the six target-flanker distances. Error bars represent +/-1 standard error of the mean.

As can be seen in Figure 22, the effect of masking did not subside with the largest target-flanker distance in the crowded condition. As such, the seeming distance over which the flankers influenced OSM seems to be far broader than was anticipated to occur with this experiment. When looking at the effect of crowding on OSM (see Figure 22, plate C) it can be seen that this effect is abolished in Experiment 9. That is, the masking effect produced in the crowded and uncrowded conditions completely converge. However, as in Experiment 8, this is largely because of changes in the uncrowded condition. In other words, it seems that the level of masking is being influenced by what happens some distance away from the target.

It can be argued that the distinction between the uncrowded and crowded conditions in this experiment is an arbitrary one. Essentially in the design of this experiment anything which was within +/-90° of the target was treated as a crowded trial and anything outside of this 180° range is treated as an uncrowded trial. Though essentially arbitrary this is the same design used in the last two experiments. Here however – because of the extended range of target-flanker distance– at the largest distance (4.9°) the crowded and uncrowded conditions are almost equivalent in terms of the position of the flankers in relation to the target.

Given this issue, the analysis conducted, though following on from Experiments 7 and 8 may not be the most appropriate for revealing the nature of the effect of target-flanker distance on OSM. Given the essentially continuous nature of target-flanker distance in this experiment it may be more profitable to plot and analyse this variable in this manner instead of with the arbitrary crowded-uncrowded distinction. Thus a further analysis of the data was conducted in which crowding was treated as a continuous variable of *target-flanker distance.* This was done in order to get a better picture of the nature of the change in the masking effect with this manipulation. Thus target-flanker distance was of the following six distance conditions: 0.63°, 3.02°, 4.90°, 7.35°, 9.23°, and 11.62° of visual angle. These distances correspond respectively with 0.2, 0.8, 1.3, 1.9, 2.4 or 3.0 times the target eccentricity.

The mean percent correct responses in each factorial condition of mask duration and target-flanker distance are shown in Figure 23(A). These are the same data as in Figure 22 but plotted on a continuum of target-flanker distance. Analysis was conducted using a 2×6 repeated measures ANOVA with *mask duration* (0;180) and *target-flanker distance* (0.63°; 3.02°; 4.90°; 7.35°; 9.23°; 11.62° of visual angle) as the two variables of interest. Significant main effects were found for *masking* and *target-flanker distance*: $F[1, 31]=712.52$, $MS^{error}=148.80$, $p<.001$, $\eta_p^2=.96$ and $F[5, 155]=248.40$, $MS^{error}=53.93$, $p<.001$, $\eta_p^2=.89$ respectively. A significant interaction was also found between the two variables: $F[5, 155]=411.93$, $MS^{error}=55.41$, $p<.001$, $\eta_p^2=.11$. With the log transformed data, the pattern of results for the target-flanker distance×mask duration interaction did not change ($F[5, 155]=3.26$, $MS^{error}<0.01$, $p=.008$, $\eta_p^2=.10$).

These findings indicate, firstly, that masking and crowding each independently reduce performance in terms of the ability to identify a digit. In addition to this there is a clear interactive effect between masking and target-flanker distance. This effect was not, however, in the form that was predicted. It was predicted that OSM would be most affected at the smallest target-flanker distances and would diminish with increasing distance. That is, the decline in OSM was expected to be monotonic with the largest effects being seen at the smallest target-flanker distances. Rather, what was found was that masking appears to present with an inverted U-shaped function against target-flanker distance where the effect of crowding on OSM is most apparent at the middle distances with weaker masking produced at the nearest and furthest target-flanker distances. As can be seen in Figure 23, the multiplicative effect on performance that can be produced by the combined use of the two phenomena is most effective at medium target-flanker distances (3.02°). In line with this, ANOVA results found the *mask duration×target-flanker distance* interaction to be highly significant with respect to the polynomial tests for a quadratic function ($F[1, 31]=10.42$, $MS^{error}=26.57$, $p=.003$, $\eta_p^2=.25$.

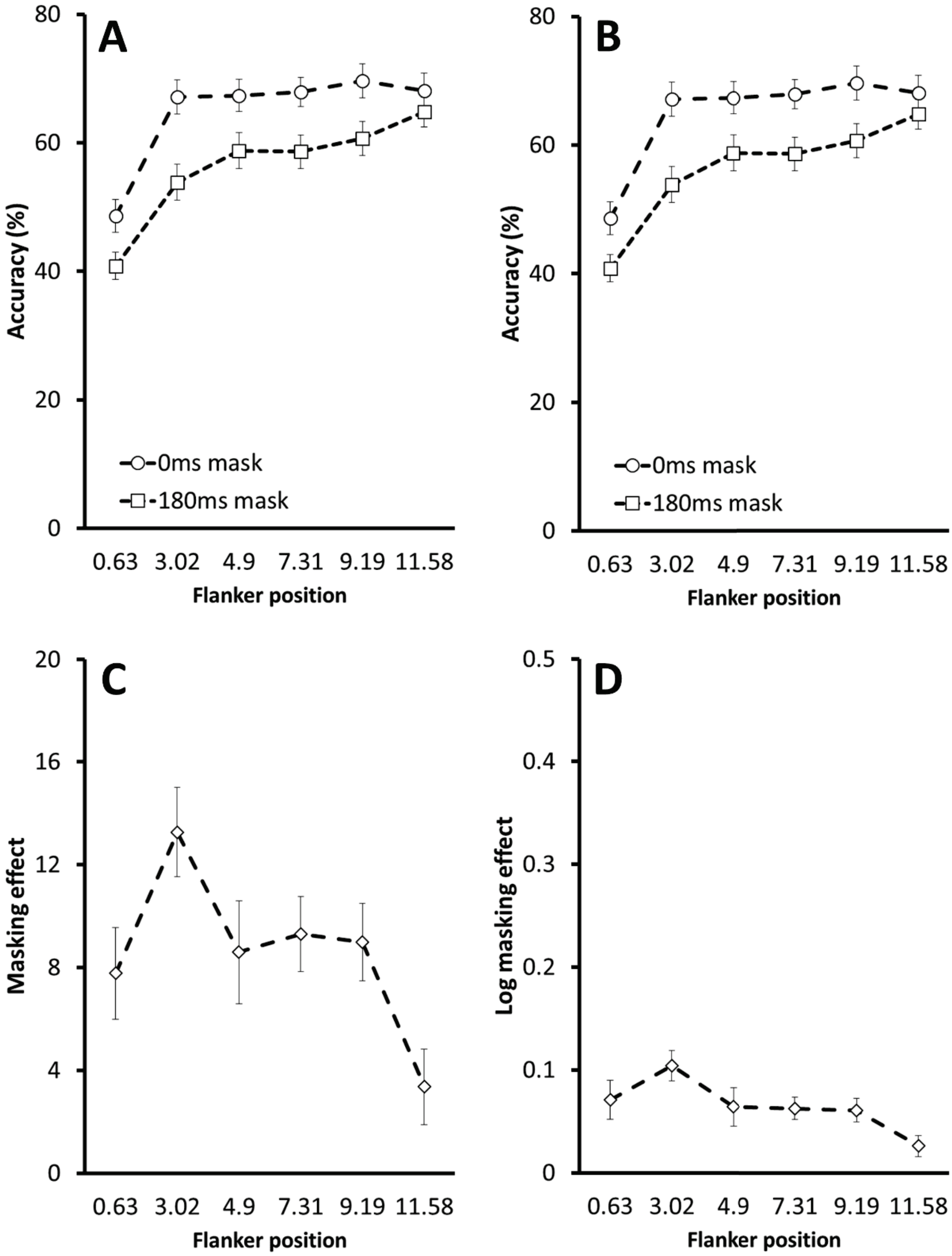

Figure 23| Performance in Experiment 9 (extended target-flanker distance). The figure shows accuracy (% correct; plate A) and transformed accuracy (Log10; plate B for the six target-flanker distances by each of the two mask duration conditions (0, 180ms). Plate C shows the masking effect for the accuracy data and plate D shows the masking effect for the transformed accuracy data (difference between 0ms and 180ms mask duration) across the six target-flanker distances. Error bars represent +/-1 standard error of the mean.

Discussion

Experiment 9, like Experiments 7 and 8 showed that crowding as a variable – in addition to reducing overall target perceptibility – also influenced the size of OSM. This experiment, in having a more extended range of target-flanker distances, made it easier to discern the relationship between OSM and target-flanker distance. Given the unanticipated wideness of the range of the effect of the target-flanker distance variable, the nature of the relationship with masking was most obvious when the target-flanker distance variable was treated as a single continuum.

When the data were presented in these terms it was most clear that the data did not conform well to the predictions made. Rather than the effect of crowding on masking being most apparent at the smallest (0.63°) target-distractor distance and monotonically declining thereafter as predicted, the masking pattern (as seen in Fig. 23) demonstrated a marked inverted 'U' shape function. The presence of this function was confirmed by the existence of a significant quadratic trend in the ANOVA analysis. It can be seen that the masking effect was strongest at a target-flanker distance of 3.02°. Importantly this distance is well beyond that of Bouma's (1970) critical spacing window of half the display eccentricity (1.95°). In fact, this distance occurs at approximately 0.8 times the display eccentricity.

Though the pattern of the interaction was unexpected, the finding is not without precedent within the crowding literature. As described earlier Vickery et al (2009) also explored interactions between masking and crowding. Unlike the current experiments, the interest of Vickery et al was on understanding crowding rather than masking per se. Nevertheless, Vickery and colleagues examined the interaction between masking and crowding (see section 3.1.6).

Vickery and colleagues (2009) found that when the target was unmasked a standard crowding function was observed. That is, strong crowding was produced at the closest target-flanker distance and greatly reduced as the distance increased. When the target was masked however, the crowding function was extended. That is, crowding was still produced at the largest target-flanker distance, far outside the range expected to produce crowding according to Bouma's law (1970; see Figure 13). They argued that this "supercrowding" effect resulted from masking of the target causing it to become more vulnerable to crowding over a larger spatial range. They interpret this effect as the interactive effect of masking on crowding. In the current experiments the pattern of results is explained in terms of the effect of crowding on masking i.e. at what target-flanker distance the target becomes most vulnerable to OSM.

There is another way to think about the Vickery and colleagues' (2009) data however; that being from the perspective of the change of the masking effect with respect to variations in crowding distance. The relevant comparison made here would be in terms of the performance on unmasked and masked trials. When the data are looked at in this manner there seems to be an inverted U-shaped function (it is somewhat difficult to assess the full character of this function in Vickery et al's (2009) data as only three target-flanker positions are given). This function shows relatively weak masking with flankers at the nearest (0.3) and furthest (0.7) position to the target, (as well as strongest masking occurring at the middle (0.5) target-flanker distances). When the findings of the Vickery et al study are examined in this way, they present a rather similar overall pattern to that observed in the current experiment in terms of masking. That is, masking is strongest at a middle target-flanker distances with much weaker masking at the near or far distances. Thus, although this finding was unexpected in this series it is in fact in keeping with at least one study in the previous literature.

3.5 Experiment 10: Crowding interactions at higher eccentricities

Experiment 10 was carried out for two reasons. The explanations given of the finding in Experiment 9 were somewhat post hoc in nature. The data pattern, although interpretable in terms of previous literature, was not in the form which was originally predicted. That is, the predicted monotonic decline in the effect of flankers on masking with increasing target-flanker distance did not occur. Rather, the pattern was clearly non-monotonic in nature. Thus one reason for Experiment 10 was to determine if the non-monotonic effect of flanker distance on masking would replicate under different conditions. This is particularly pertinent given the fact that the claim of a non-monotonic function of the interaction between OSM and crowding, in this experiment, is essentially based on the position of a single data point (if the amount of masking in the target-mask 3.02˚ condition was somewhat lower then the trend would appear monotonic in the manner predicted). Given this, it seems reasonable to determine if this is a mere statistical anomaly of Experiment 9 or whether it is a robust characteristic of the interaction.

A second reason for conducting Experiment 10 was to examine if the interaction between crowding and OSM would exhibit a hallmark associated with crowding, that of it scaling with eccentricity. The distance and strength at which flankers effectively crowd the target increases with target and flanker eccentricity (with respect to fixation; Gurnsey et al., 2011; Huckauf & Heller, 2004; Pelli et al., 2004). Given this, it was predicted that more prominent crowding effects would be found with stimuli presented at a larger eccentricity than given in the previous experiment. Of interest was whether this presumed increase in overall crowding would make the crowding×OSM interaction even more pronounced and perhaps even greater in its spatial extent. In order to explore the effect of OSM in more detail an additional, intermediate mask condition (60ms delayed mask) was included. It was hoped that the addition of this condition would provide a fuller understanding of the relationship between crowding and masking than was uncovered in Experiment 9.

This experiment was conducted in two parts (Experiment 10a; Experiment 10b), in which the stimulus array was presented at an eccentricity of 4.75° and 5.4° respectively (greater eccentricities were tested but tended to lead to near chance performance in some conditions making it difficult to understand the masking function). This compares with the 3.9° eccentricity given in Experiment 9.

Thus, as with Experiment 9, it was predicted that masking would display an inverted U-shaped function with respect to target-flanker distance. Given the effect of eccentricity on crowding, it was expected that the form of this inverted U-shaped function would change across the two eccentricities. That is, it was expected that peak masking would occur at a greater target-flanker distance than observed in Experiment 9; the peak shifting further from the target with each increase in eccentricity.

The target-flanker distances used were kept constant across the two eccentricity displays. This was done to examine if there was an increase in the range with which crowding would sufficiently interact with OSM as eccentricity increased. An additional target-flanker distance was added to Experiment 10b to account for the increased circumferential display size with the 5.4° eccentricity given that the target-flanker distance was kept constant across the two parts of the experiment.

This experiment aimed firstly to confirm whether the interaction between masking and crowding does exhibit an inverted U-shaped function or if in fact it is an artifact of the stimulus conditions of Experiment 9. Secondly, given the fact that crowding increases in strength and has a wider range with increased eccentricity, this experiment aimed to examine if differences in this inverted U-shaped function would occur across eccentricities. Specifically, it was expected that the peak masking effect would occur at proportionally larger target-flanker distances with increased eccentricity.

3.5.1 Experiment 10a: medium eccentricity (4.75°)

This experiment had three mask duration conditions (0, 60, 180ms) and seven conditions of target-flanker distance (1°, 3°, 5°, 7°, 9°, 11°, 13°). It was expected that, consistent with the crowding literature, the smallest given target-flanker distance condition (1°) would produce the strongest crowding (as measured on unmasked trials) with crowding monotonically declining as target-flanker distance increased. What is of interest is what happens on masking trials. It was expected that this difference in crowding would be manifested in a masking function in which OSM (as measured by the effect of mask duration) would be strongest at the medium target-flanker distances and decline with small or large distances as was found in Experiment 9 and by Vickery et al (2009).

Method

Participants

Twenty-two undergraduate and postgraduate Oxford Brookes Psychology students (17 female) took part in the experiment. All participants gave informed consent. Undergraduate students received course credits for completing the experiment. All participants reported normal or corrected-to-normal visual acuity.

Stimuli and procedure

The stimuli and procedure were identical to those of Experiment 9 (see section 3.5) except where stated. The eccentricity of the display was 4.75° of visual angle (increased from 3.9° in the previous experiments). The number of mask durations used was increased to three (0, 60, and 180) in an attempt to give a more psychophysical presentation of the masking data (i.e. a more in depth study of the relationship between the effect of masking on the target and its perception). The number of target-flanker distances was increased to seven: 1°, 3°, 5°, 7°, 9°, 11° and 13° of visual angle. These distances correspond with 0.2, 0.6, 1.1, 1.5, 1.9, 2.3

and 2.7 times the target eccentricity. These target-flanker distances were presented on a continuum as with Experiment 9 (i.e. no separate conditions of uncrowded and crowded; see Figure 24 where the “3” is the target).

There were 630 trials, 30 trials for each combination of *masking* and *target-flanker distance*. The trials were presented within 10 distinct blocks. Participants were asked to take a break after each 63 trial interval.

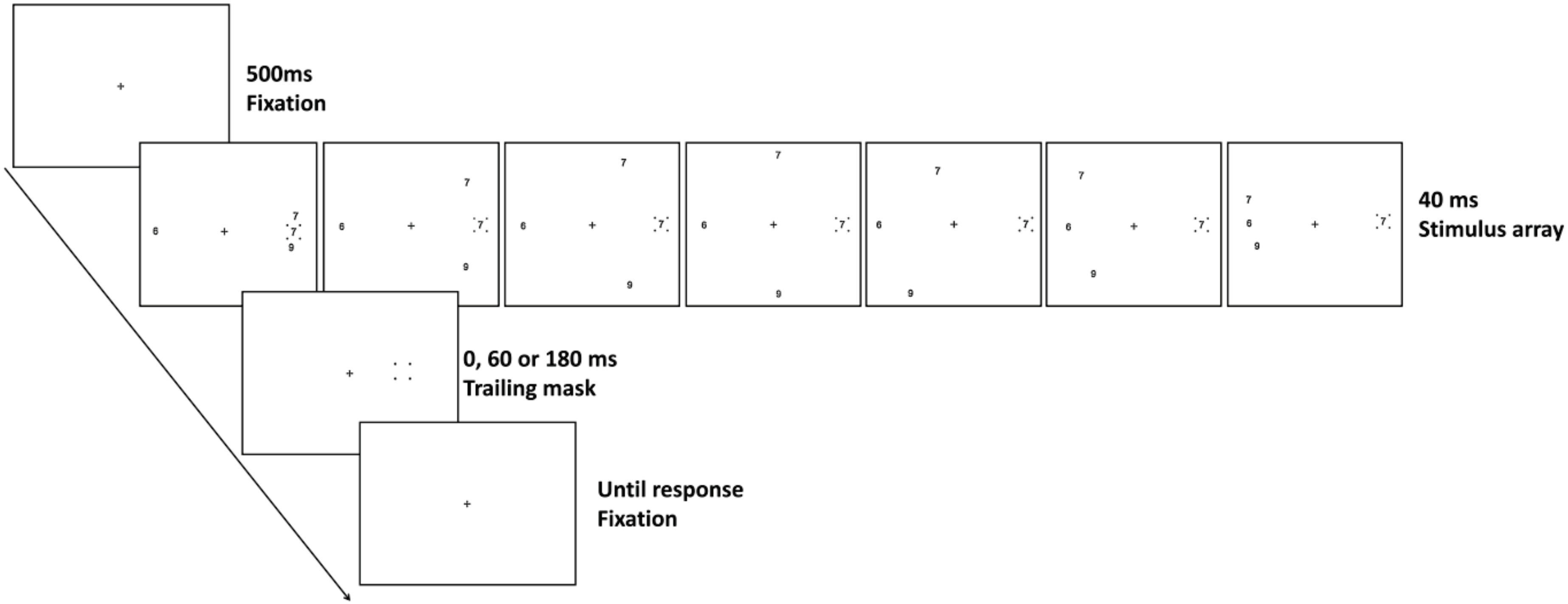

Figure 24| A schematic depiction of the trial sequence in Experiment 10a (4.9° eccentricity). The seven stimulus array frames depict examples of trials for (from left to right) a target-flanker distance of 1°, 3°, 5°, 7°, 9°, 11° and 13°.

Results

The average percent correct responses in each factorial condition of mask duration and target-flanker distance are shown in Figure 25(A). These data were analysed using a 3×7 repeated measures ANOVA with *mask duration* (0; 60; 180) and *target-flanker distance* (1°; 3°; 5°; 7°; 9°; 11°; 13° of visual angle) as the two variables of interest. Significant main effects were found for *masking* and *target-flanker distance*: $F(2, 42)=31.48$, $MS^{error}=85.31$, $p<.001$, $\eta_p^2=.60$ and using Greenhouse-Geisser correction, $F(6, 126)=23.52$, $MS^{error}=7.77$, $p<.001$, $\eta_p^2=.53$ respectively. Given the results of Experiment 9 showed that the effect of masking peaked at medium target-flanker distances an inverted U-shaped function was expected for the current experiment. Specifically, a quadratic (inverted U-shaped) function was expected for the *masking*×*crowding* (target-flanker distance) interaction. As such, the significant quadratic function of the interaction is reported: $F(1, 21)=10.98$, $MS^{error}=43.57$, $p=.003$, $\eta_p^2=.34$ (see Figure 26[C]). In contrast, the linear function of the interaction was not significant: $F(1, 21)=0.32$, $MS^{error}=86.33$, $p=.580$.

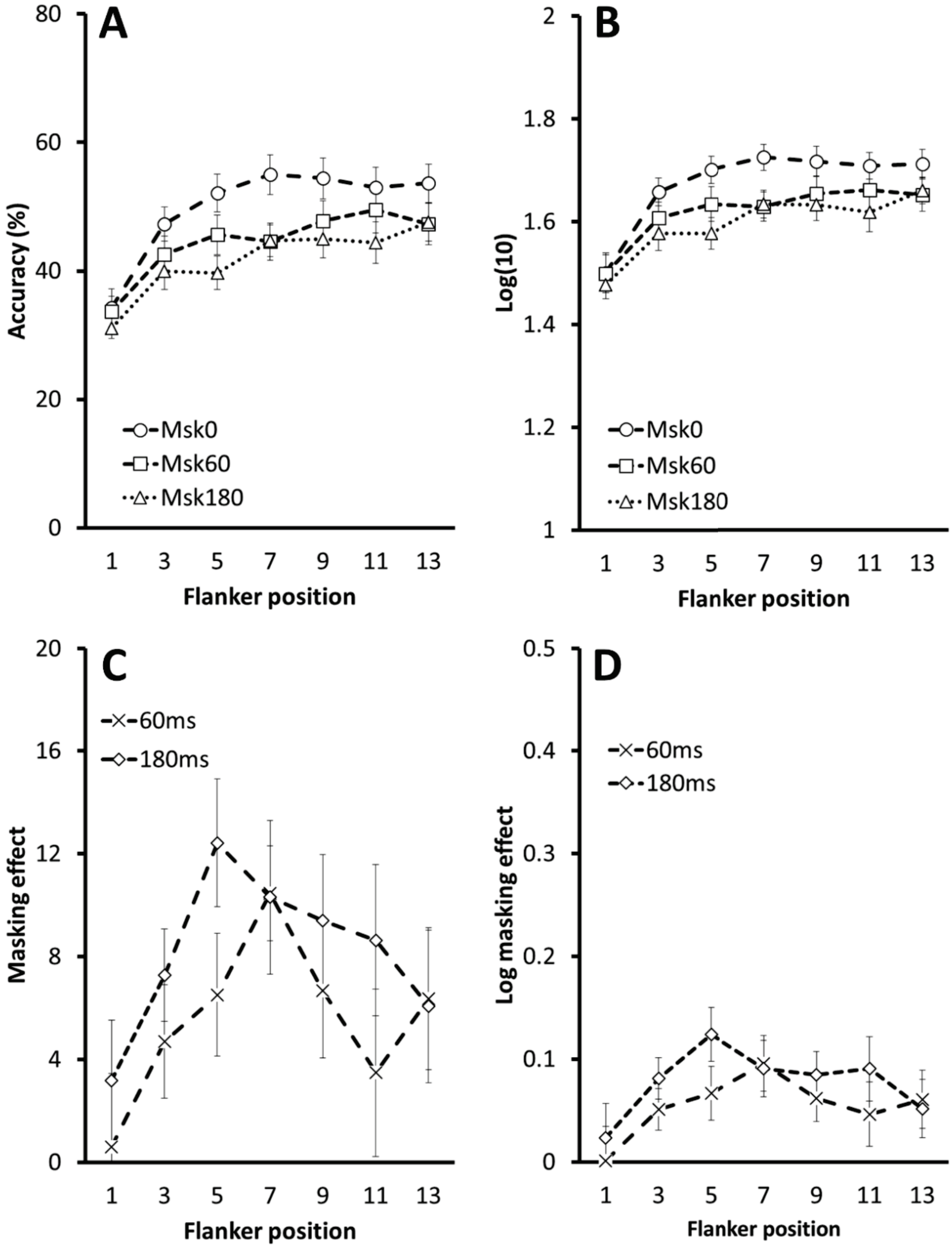

Figure 25| Performance in Experiment 10a (4.9° eccentricity). The figure shows accuracy (% correct; plate A) and transformed accuracy (Log10; plate B for the seven target-flanker distances by the three mask duration conditions (0, 60, and 180ms). Plate C shows the masking effect (difference between 0ms and 60ms and 0ms and 180ms mask duration respectively) for the accuracy data and plate D shows the masking effect for the transformed accuracy data across the seven target-flanker distances. Error bars represent +/-1 standard error of the mean.

3.5.2 Experiment 10b: large stimulus eccentricity (5.4°)

Method

Participants

Twenty-two participants were recruited from Oxford Brookes University (18 female). All participants gave informed consent and received either course credits or £7 remuneration for completing the experiment. All participants reported normal or corrected-to-normal visual acuity.

Stimuli and procedure

The stimuli and procedure were identical to those of Experiment 10a (see section 3.6.1) except where stated. The eccentricity of the display was increased to 5.4° of visual angle. An additional target-flanker distance was added compared to Experiment 10a as a consequence of the increased circumferential display size at the greater eccentricity. The target-flanker distances were therefore: 1°, 3°, 5°, 7°, 9°, 11°, 13° and 15° of visual angle. These distances correspond with 0.2, 0.6, 0.9, 1.3, 1.7, 2.0, 2.4 and 2.7 times the target eccentricity. There were 720 trials, 30 trials for each combination of masking and target-flanker distance. The trials were presented within 10 distinct blocks. Participants were asked to take a break after each 72 trial interval.

Results

The average percent correct responses in each factorial condition of mask duration and set size are shown in Figure 26(A). These data were analysed using a 3×8 repeated measures ANOVA with *mask duration* (0; 60; 180) and *target-flanker distance* (1°; 3°; 5°; 7°; 9°; 11°; 13°; 15° of visual angle) as the two variables of interest. Significant main effects were found for *masking* and *target-flanker distance*: $F(2, 42)=20.96$,

MS^{error}=102.75, p<.001, η_p^2=.50 and F(7,147)=51.12, MS^{error}=67.01, p<.001, η_p^2=.71 respectively. The quadratic function of the interaction between masking and crowding was also significant, F(1, 21)=10.75, MS^{error}=64.09, p=.004, η_p^2=.34. In contrast, the linear function of the interaction was not significant: F(1, 21)<0.01, MS^{error}=74.69, p=.627.

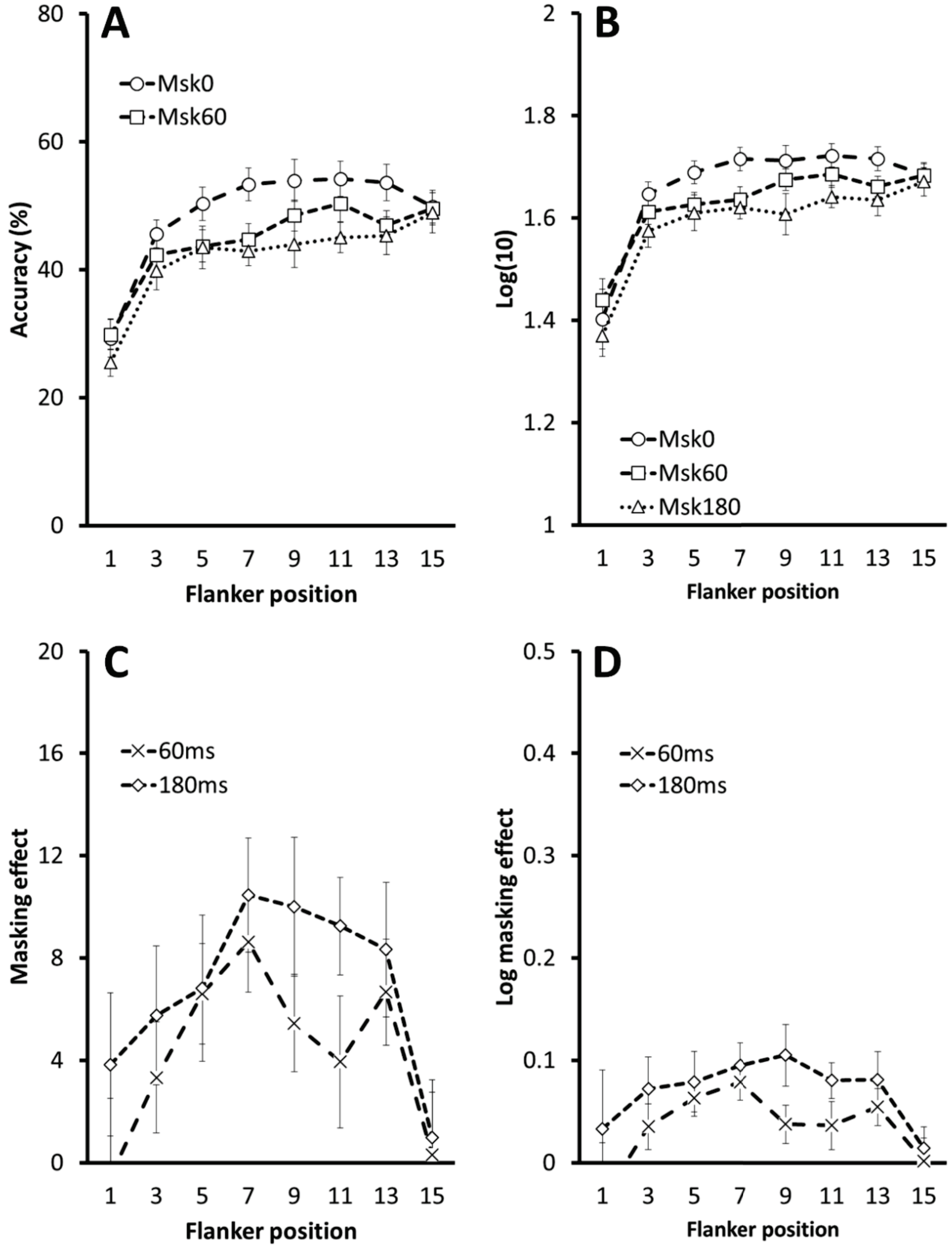

Figure 26| Performance in Experiment 10b (5.4° eccentricity). The figure shows accuracy (% correct; plate A) and transformed accuracy (Log10; plate B for the eight target-flanker proximities by the three mask duration conditions (0, 60, and 180ms). Plate C shows the masking effect (difference between 0ms and 60ms and 0ms and 180ms mask duration respectively) for the accuracy data and plate D shows the masking effect for the transformed accuracy data across the six target-flanker distances. Error bars represent +/-1 standard error of the mean.

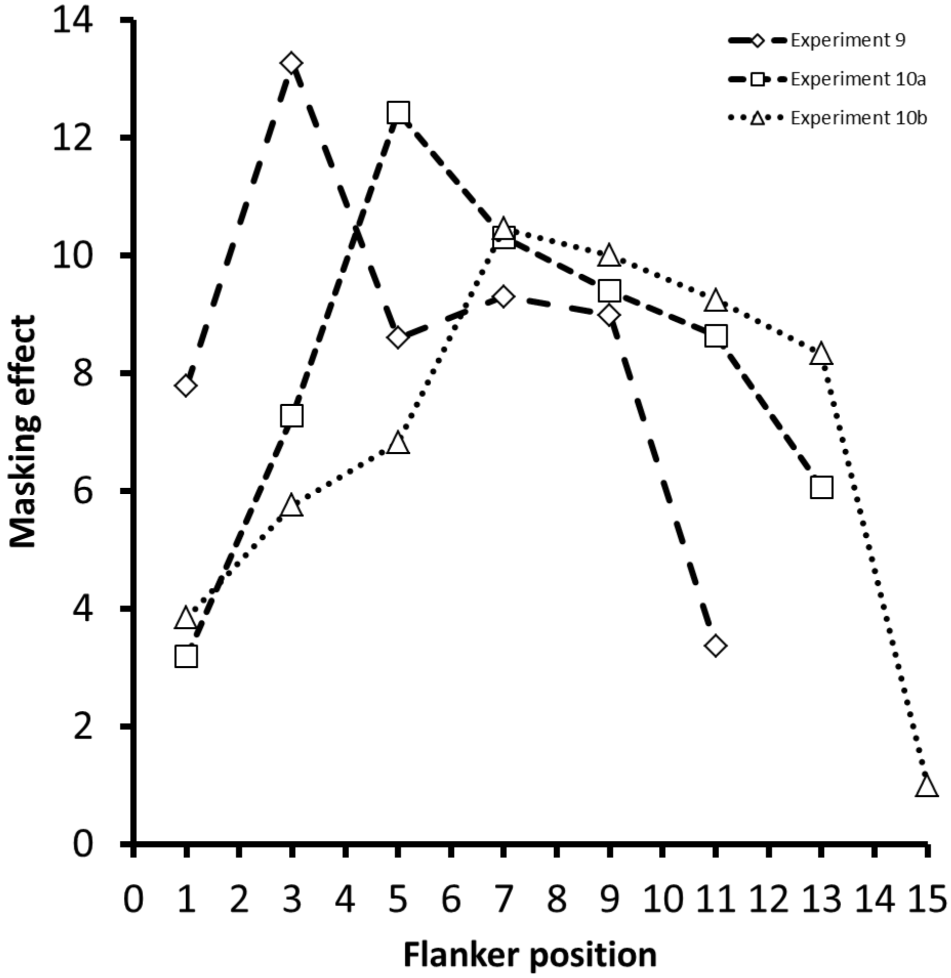

Figure 27| The masking effect (difference between 0ms and 180ms mask duration) for Experiment 9, Experiment 10a and Experiment 10b to allow easy comparison of the masking function obtained at the different eccentricities.

Discussion

A clear crowding effect can be seen in both the unmasked and masked data in that for both there is a clear reduction in accuracy associated with the smallest target-flanker distances. Moreover, for both Experiments 10a and 10b, a highly significant interaction between masking and crowding was observed. Importantly both experiments showed a clear inverted U-shaped function with respect to the masking pattern (see Figure 27). Thus, as was shown in Experiment 9, masking was strongest at a mid target-flanker distances. Unlike in Experiment 9, the results could not be explained as a consequence of a single anomalous data point. The non-monotonic nature of the interaction was much more apparent.

The implications of these findings, in particular with regard to the non-monotonic nature of the crowding×masking interaction will be discussed in more detail in the general discussion of this chapter. From visual inspective of Figure 27, there is some indication that there was a relative delay in the stage at which greatest OSM occurred. That is, the largest masking effect appears to occur later in Experiment 10a (5˚) than in Experiment 9 (3.02˚). This masking effect then seems to be further delayed for Experiment 10b (7˚).

3.6 General Discussion

The experiments conducted in this chapter started by examining whether the set size effects on OSM found in Chapter 2 were indeed a consequence of set size (i.e. the number of distractors present in the display) or whether there was an alternative explanation, that of crowding of the target. The first experiment was conducted to establish if crowding effects could be produced with the circumferential displays used in Chapter 2. This experiment found substantial crowding when the distractors were presented close to the target while crowding was not produced when the distractors were presented opposite the target in the circumferential display.

Once it was clear that crowding could be observed in these types of displays, Experiment 7 explored the effects of crowding and set size independently in an OSM paradigm. That is, set size, target-distractor distance and mask duration were all independently manipulated. The results of this experiment showed that crowding and set size were able to be experimentally dissociated from each other. Set size was found to have a clear effect on overall performance but had no influence on OSM. Crowding, in contrast, interacted with mask duration as well affecting overall target perceptibility. That is, greater OSM was produced when the distractors closely flanked the target compared to when they flanked a location opposite the target. Thus, crowding alone and not set size was shown to influence OSM.

From this point, three experiments were conducted to assess the nature of the interaction between OSM and crowding. Experiment 8 examined the distance at which distractors impact OSM. That is, this study manipulated target-flanker distances in the aim of finding the point at which OSM showed a substantive reduction. The findings of this study replicated the effect of crowding on OSM in terms of the comparison between crowded and uncrowded conditions. It was found that the target-flanker distance at which the influence of distractors occurred far exceeded what was anticipated, or what was used to investigate crowding in Experiment 8. Experiment 9 therefore extended the range at which the target-flanker distances were investigated. This experiment revealed that the interaction between OSM and crowding was wide ranging and continued far outside the critical spacing window proposed by Bouma (1970). The crowding effect on masking also seemed to exceed the spatial extent of crowding that was exhibited on the unmasked trials.

In Experiment 9 the crowded and uncrowded trial variable was, as stated earlier, somewhat arbitrary given that the distances used in this study encompassed the entire circumferential distance of the stimulus array. Thus the target-flanker distances could be plotted as a single continuum. When this was done the pattern of the interaction between crowding and masking became more apparent. This function did not display the expected monotonic decline in crowding on masking as target-flanker distance increased. Rather there was a clear but unexpected nonmonotonic, inverted U-shaped function in the pattern of masking. That is, the magnitude of OSM was minimal at the small or large target-flanker distances while being substantial at the medium target-flanker distances.

The final experiment, Experiment 10, was conducted in two parts to examine if the effect of OSM would scale with eccentricity (one of the hallmarks of crowding). This study also aimed to establish if the inverted U-shaped function of the interaction between OSM and crowding was a reliable one. This study presented seven and eight target-flanker distances in the two parts respectively at two wider eccentricities than in Experiment 9. An interaction between OSM and crowding was again observed. In both parts of the experiment the interaction expressed itself as an inverted U-shaped function, as found in Experiment 9. The magnitude of the interaction was not found to differ greatly across the two eccentricities.

3.6.1 The effect of set size in OSM

The results of Experiment 7 showed that set size itself is not a relevant variable in OSM, though it is one that affects overall target perceptibility. These findings indicated that the set size effect reported in Chapter 2 could in fact be explained as an artifact of crowding of the target with increased set size. That is, in Chapter 2 target-flanker distance naturally decreased as set size increased. When set size and crowding were measured independently of one another, as was done in Experiment 7, it became evident that set size did not interact with OSM as was previously indicated. Rather, it was found that set size had an effect only on overall perceptibility of the target whereas crowding was found to substantially increase the effect of OSM. The impact of these results for the OSTM and their relation to previous literature on OSM will be discussed in Chapter 5.

3.6.2 The effect of crowding in OSM

The results of this series, and in particular of Experiment 6, show that crowding occurs with the circumferential displays and digit stimuli used in this thesis. That is, when the distractors were presented at a location close to the target overall target perceptibility was reduced when compared against a condition in which distractors were placed on the opposite side of the screen to the target.

In addition to the overall performance impairment produced by crowding, the results of this series showed that crowding repeatedly interacted with OSM. Experiments 7 and 8 expressed this as increased OSM with small target-flanker distances. From Experiment 9 onwards this interaction was revealed to be more complicated. That is, the interaction between OSM and crowding was found to be a nonmonotonic, inverted U-shaped one. To specify, small amount of OSM were produced at the closest target-flanker distance or at the large target-flanker distances. At medium target-flanker distances however there was a substantial increase in masking magnitude.

The findings of the current series indicated that this effect of OSM occurred outside the range expected to produce crowding. To recap, there is a general expectation in crowding that flankers that are more than 0.5 times the target eccentricity away from the target will not produce crowding (Bouma, 1970). The findings presented here show that under conditions of OSM, the distance at which flankers impacted performance far exceeded this range. The peak effect of the interaction between OSM and crowding occurred at a distance of 0.8, 1.1 and 1.3 times the target eccentricity for the 3.9°, 4.75° and 5.4° target display eccentricities respectively.

This can be viewed in two ways. Firstly, this interaction can be viewed as increased OSM at the medium target-flanker distances as it has been up to this point. Secondly, this finding can be viewed as OSM effectively widening the distance at which crowding (surrounding flankers) has a substantive effect on target perceptibility. Given the inverted U-shaped function of the interaction between crowding and OSM, it is perhaps more likely that the latter of these explanations fits the data. Thus, rather than the interaction between crowding and OSM representing an effect of crowding on OSM as expected, it appeared that it actually represents an effect of OSM on crowding. This issue and its theoretical implications will be discussed in more detail in Chapter 5.

These findings show parallels with those of Huckauf and Heller (2004). The results of the current series of experiments revealed a non-monotonic increase in OSM with increased target-flanker distance. That is, the effect of masking was strongest at medium target-flanker distances. Conceivably, at these distances the effect of classical crowding was weaker than at the close target-flanker distances meaning that OSM was able to extend the range at which flankers had an effect on target perceptibility. Huckauf and Heller also found a non-monotonic effect of masking. They found that when the target-flanker distance increased beyond a narrow range the effect of masking produced an inverted U-shaped function. Specifically, they found that for medium and large target-flanker distances the effect of masking was most prominent at an SOA of 50ms. In other words, the additional impact of masking was greatest when the flankers onset 50ms after the target. The findings of this chapter also show particularly apparent similarities to the "supercrowding" phenomenon presented by Vickery and colleagues (2009) as discussed in section 3.5.

A further finding of the current series of experiments was that crowding was roughly equal at the closest target-flanker distance under masked and unmasked conditions i.e. there was no effect of OSM at this closest distance. These findings again show parallels with those of Huckauf and Heller (2004) and Vickery et al (2009). They also found that within the typical crowding window, the performance impairment was equal across conditions of masking i.e. there is no obvious effect of masking at close target-flanker proximities. These findings suggest, as was claimed by Vickery and colleagues, that at this closest target-flanker distance, the effect of crowding is perhaps overpowering. Crowding has been shown to produce a stronger impairment on target perceptibility than OSM (Breitmeyer, 2015) and as such may have dominated the impairment produced at those closest target-flanker distances.

It is worth noting that the paradigms of both Huckauf and Heller (2004) and Vickery et al (2009) were markedly different from that used in the current series. For instance, the paradigm used by Huckauf and Heller included no additional mask: masking was examined based on the SOA of the flankers. The two flankers alone acted as the mask when they onset asynchronously with the target. The type of mask used by Vickery et al was predominantly a low level, surround mask instead of the 4DM used in the current series.

A major component of OSM is that the mask trails the target offset whereas the mask onset and offset with the target in the Vickery et al (2009) study. Furthermore, in the Vickery et al study the target and flankers were all Ts presented in one of four orientations, the location of which were set within the top half of the display. In contrast, the current studies used heterogeneous digit stimuli that were presented randomly on a notional circle. Given such substantial differences between these paradigms it is particularly striking that a rather similar pattern of results was produced.

The current findings also suggest that the interactive effect of crowding and masking is not simply attributable to low level contour interactions or additional crowding by the mask itself, a factor that

Vickery et al (2009) went to some lengths to disprove as a possible alternative explanation of their data. The mask used in OSM consists of only four dots (and thus contains only minimal contour and has a structure that is highly dissimilar in nature to the target). This means that, as others have argued (e.g. Enns & Di Lollo, 2002) the likelihood of significant contour interactions occurring between the 4DM and the target is minimal. Furthermore, the masking effect that occurs with OSM itself has also been shown to be relatively unaffected by contour manipulations (Enns, 2004; Guest, Gellatly & Pilling, 2011).

Given that this chapter produced a robust and reliable interaction between crowding and OSM, the processes underlying this interaction need to be better understood. Crowding has been argued to be a relatively low-level phenomenon with respect to OSM (Breitmeyer, 2014; Wilkinson et al., 1997). If, as is suggested here, OSM is influencing crowding (rather than crowding influencing OSM) then this observation is inconsistent with OSM's position in this putative hierarchy of visual processing phenomena (Breitmeyer, 2014).

One useful technique for trying to discern the temporal aspects of stimulus processing is the EEG/ERP technique. Electrophysiological recordings of brain function could be useful in giving further indication of whether the findings relate to an effect of crowding on OSM or an effect of OSM on crowding and in understanding the stage in which the interaction between OSM and crowding occurs. The employment of such a method is the subject of the next chapter.

3.7 Chapter summary

The five experiments conducted in this chapter aimed to explore whether the ostensible set size effect found in Chapter 2 could be explained by another factor, that being crowding. Experiment 6 in this series was conducted to discover if crowding of the target was possible in the circumferential displays used in Chapter 2, irrespective of masking. This experiment found strong crowding when distractors were presented close to the target and minimal crowding when distractors were presented at a location opposite the target. As this experiment found an effect of crowding, Experiment 7 was conducted to investigate the effects of crowding and set size independently on OSM. The results of this experiment showed that contrary to what was found in Chapter 2, set size did not have an effect on OSM. In contrast, only crowding had an effect on OSM. Thus, when set size and crowding were investigated independently, set size had an effect on overall target perceptibility whereas crowding increased OSM.

From this point, the effect of crowding on OSM was further investigated. Experiment 8 aimed to establish if the interaction between OSM and crowding could be replicated when set size was removed as a factor. Furthermore, this study examined the spatial range in which this effect of crowding on OSM occurs in terms of target-flanker distances. The results of this study again showed an interaction between crowding and OSM. This interaction was also found to be more wide ranging than was expected. That is, the interaction between crowding and mask duration continued at the largest target-flanker distance presented. Experiment 9 was therefore conducted to examine the point at which this interaction diminishes. Experiment 9 extended the range of the target-flanker distances investigated. This experiment again produced an interaction between OSM and crowding. The interaction produced in this study revealed an unexpected inverted U-shaped function. That is, the effect of masking was most prominent at medium target-flanker distances while little additional impairment from masking was found at near or far target-flanker distances.

From this a final study was conducted. This study first aimed to establish if the inverted U-shaped function of the interaction produced in Experiment 9 could be replicated, or if rather it was a consequence of the task conditions in that experiment. Second, this experiment was conducted in two parts over two eccentricities to establish if the interactive effect of OSM and crowding would scale with eccentricity (as is standard in crowding). Both parts of this study revealed an interaction between OSM and crowding. Each part also revealed an inverted U-shaped function of the interaction. This inverted U-shaped function again represented masking being most prominent at medium target-flanker distances. These findings therefore showed marked similarities to those of "supercrowding". As such, this indicated that perhaps this interaction between OSM and crowding represents an effect of OSM on crowding whereby the window of crowding is increased rather than an effect of crowding on OSM, as predicted.

The question now is at what stage this interaction between crowding and OSM occurs. Crowding has been argued to occur earlier in the object processing stream than OSM (Breitmeyer, 2014) and be largely dependent on (low level) pooling between the target and flankers (Wilkinson et al., 1997). OSM in contrast is argued to be a high level phenomenon that relies on the spread of attentional resources and re-entrant processing to occur (Di Lollo et al., 2000). The next chapter describes the use of electrophysiological recordings to try to understand the temporal order of the effect of OSM, crowding, and OSM×crowding on visual processes as revealed by visual evoked potentials.

Chapter 4| An investigation into the electrophysiological correlates of OSM and crowding

4.1 Introduction

Chapter 3 was able to behaviourally demonstrate a clear interactive relationship between masking and crowding that is best conceived as an effect of masking on crowding, rather than the converse. However this claim would be stronger if it could be supported by another source of evidence. This is particularly in light of the fact that the claim is contrary to some recent theoretical assumptions about the relative positions of OSM and crowding within the object processing hierarchy (Breitmeyer, 2014; Breitmeyer, 2015; Chakravarthi & Cavanagh, 2009).

In order to gain a better insight into the effect of crowding and OSM on perceptual processing and an understanding of the relative placement of crowding and OSM in the object processing hierarchy one thing that can be done is to use the EEG/ERP technique. Such an investigation of the underlying electrophysiology of this interaction between OSM and crowding would be a logical development for understanding the underlying processing impairments caused.

This chapter will firstly briefly discuss the Electrophysiological (EEG) method and the associated Event Related Potential (ERP) technique. It will then briefly describe the typical ERP components which are found to be associated with early visual processing and what these components are thought to represent in terms of perceptual/cognitive operations. After this the chapter will review the extant literature on EEG relating to the phenomena of OSM and crowding. An EEG experiment is then described.

This experiment had several aims. Firstly, it attempted to replicate some of the electrophysiological correlates of OSM and crowding which have been reported in the literature previously. These literatures are rather small and are in need of further evidence on the nature of these supposed EEG signatures of OSM and crowding. Secondly the experiment attempted to determine if there are clear EEG correlates of conscious perceptibility of a stimulus. Both OSM and crowding can be considered as phenomena of consciousness; in their different ways, both reduce the likelihood of a target being consciously perceived. By comparing ERP responses to trials where the target was and was not consciously perceived (based on the correct and incorrect responses on the trials) it is possible to see if there is any general ERP component associated with the target being perceived.

The ERP components chosen for investigation were based on the existing literature which has argued certain components to be associated with conscious perception. A third aim of this EEG study was to try to understand the relationship between OSM and crowding in terms of changes in the earliest deflections the two respective phenomena produce in the ERP responses. Finally, a fourth aim of the ERP study was to attempt to find out if any specific neural correlates could be found of the observed psychophysical interaction between OSM and crowding, which is interpreted here as a “supercrowding” effect.

4.1.1 A brief description of the EEG technique in vision research

EEG, and in particular the ERP technique has been seen as a useful way of informing about neurophysiology and providing a physiologically plausible way of testing human perception and attention (Woodman, 2010). A major advantage of the EEG technique in comparison to many other methods is its precise temporal resolution (Luck, 2014). EEG has millisecond precision in its temporal resolution (Luck, 2014; Woodman, 2010) whereas fMRI for example has a temporal resolution in the region of 3-5 seconds (Volkow, Rosen & Farde, 1997). Thus EEG is particularly suited to understanding the temporal nature of changes in brain states. This is particularly the case when EEG is able to be analysed in terms of the temporal window of brain activity that immediately follows the presentation of a stimulus. A discussion of such ERPs in the context of visual stimulus processing is given in the next section.

4.1.2 An introduction to visual ERPs

Visual ERPs can be studied by recording the time point when a visual stimulus is presented and examining the activity that occurs in the time window immediately following this, relative to a pre-stimulus baseline. ERPs are difficult to detect on a single trial basis because of other spontaneous brain activity which also produces deflections in the EEG signal. It is typically necessary to average over a large number of trials of the same kind (at least ~50-100, depending on the type of ERP under investigation) in order to obtain a good enough signal-to-noise (SNR) ratio to obtain reliable ERPs (Luck, 2014; Woodman, 2010). In the averaging process the spontaneous brain activity tends to average out since this is not time locked to the stimulus event, thus increasing the SNR of the stimulus evoked activity as each additional trial is added to the average. ERPs that are specific to visual processing tend to occur within a 250ms window from stimulus onset; later ERPs tend to reflect more amodal cognitive processes associated with things such as context updating in working memory and semantic-level processing (e.g. the P3, and N400 waves; Luck, 2014).

The earliest visually evoked component found after stimulus onset is known as the *C1*. This typically occurs within 40-60ms of stimulus onset. This *C1* component is argued to reflect activity in V1 associated with the onset of a visual stimulus. The *C1* is small in amplitude compared to other, later occurring, ERPs but is largest at posterior midline electrodes (Luck, 2014). Due to the small amplitude a large number of trials (~1000) are recommended for a sufficient SNR to observe the *C1* component (Woodman, 2010). A characteristic of the *C1* is that the deflection switches polarity (positive vs. negative) based on where the evoking stimulus is presented within the visual field, i.e. upper or lower half (Chen et al., 2014; Clark & Hillyard, 1996; Luck, 2014; Woodman, 2010). This makes the *C1* unusual amongst components, most others tend to have a fixed polarity (either negative or positive and tend to be given an N or P prefix accordingly, the *C* reflects the variable nature of its polarity and it is the only ERP component with this prefix; Luck, 2014). Given these facts the C1 is typically not observed in most visual ERP experiments as the paradigm is usually not manipulated in a way to observe the C1 and the number of trials is usually far less than the minimum requirements.

It is thought that the *C1* component is generated predominantly by feedforward processing (Clark & Hillyard, 1996). That is, as the *C1* occurs within 100ms of stimulus onset it is associated with early, feedforward visual processing as opposed to re-entrant processing from higher cortical areas (Lamme & Roelfsema, 2000; see section 1.4.1 for a recap on feedforward and feedback processing).

The *C1* activation is closely followed by the *P1* and *N1* components. Both of these components are argued to represent visual sensory processing (Vogel, Luck & Shapiro., 1998). The *P1* is a positive deflection that typically onsets around 60-90ms post stimulus onset and peaks between 100 and 130ms with largest amplitude occurring at lateral occipital electrodes (Luck, 2014). The *N1* is a negative ERP that broadly occurs within a window of 100-200ms. Like the *C1* their amplitude characteristics appear sensitive to the physical characteristics of the stimuli such as luminance contrast (Johannes, Münte, Heinze, & Mangun, 1995) and spatial frequency (Pourtois, Dan, Grandjean, Sander, & Vuilleumier 2005). However these components are not completely stimulus driven and can be modulated by spatial attention, for example *P1* and *N1* amplitude is substantially larger for attended compared to unattended stimulus locations (Clark & Hillyard, 1996; Hillyard, Vogel & Luck, 1998; Luck, 2014).

Although it is broadly accepted that both *P1* and *N1* are sensitive to attentional effects, the two components can be dissociated from one another suggesting that they reflect different aspects of visual processing (Luck, Heinze, Mangun & Hillyard, 1990; Vogel & Luck, 2000). *P1* is associated with early sensory processing facilitation of items in an already attended location. In contrast *N1* seems to reflect processes associated with stimulus discrimination when it occurs within the focus of attention (Luck et al., 1990; Vogel & Luck, 2000).

The *P2* component is the next visual related ERP to occur (between 135-260ms; Montoya, & Sitges, 2006) and has a positive deflection. The *P2* elicits a larger amplitude for stimuli which contain target features, for oddball (i.e. physically deviant) stimuli in a sequence, and for infrequently occurring stimuli (Luck, 2014; Luck & Hillyard, 1994a). Increased *P2* amplitude has also been found for negative versus positive arousing pictures (Bar-Haim, Lamy & Glickman, 2005; Carretie, Mercado, Tapia & Hinojosa, 2001).

The visual awareness negativity (VAN) component is an ERP correlate that is argued to relate to subjective visual awareness (Koivisto & Revonsuo, 2010). VAN is expressed as increased negativity around 200ms post stimulus onset at posterior regions (Koivisto & Revonsuo, 2003). VAN is a difference wave. Unlike the P1 for example, VAN is only observed as the difference in the ERP activation between two conditions. VAN is increased for stimuli that reach subjective visual awareness compared to stimuli that do not reach awareness (Koivisto & Revonsuo, 2010). As such, VAN is typically found by comparing trials in which a target was correctly reported with ones in which it was not, the accuracy of responses presumably reflecting the extent to which the observer was aware of the stimulus.

Finally, the *N2pc* (N2 posterior contralateral) component is a visual component which is strongly associated with focused selective attentional deployment (Luck, 2014; Luck & Hillyard, 1994b). That is, *N2pc* is argued to represent the deployment of selective attention in which the target is selected for further processing at the exclusion of nearby distractors (Luck & Hillyard, 1994b; Woodman & Luck, 2003). Like the VAN, the *N2pc* is a difference wave which is evoked by comparing electrodes at contralateral and ipsilateral hemispheric sites with respect to the target's location in the display (Luck, 2014). As such the N2pc wave cannot typically be determined in EEG paradigms unless they have been specifically designed to isolate this component. In order to do so it typically requires displays be hemispherically symmetrical whereby the target is defined by task instruction. The difference wave is calculated by comparing the activity at hemispherically ipsilateral and contralateral sites with respect to the task-defined target (Woodman, 2010).

This *N2pc* component typically occurs within 200-300ms post stimulus onset. The *N2pc* wave is largest at posterior scalp sites and is a hemispheric ERP component. This means that the wave is observed at the hemisphere contralateral to the location of the target (attended stimulus). As such, the *N2pc* component becomes more negative at contralateral than ipsilateral scalp sites in response to the presented stimulus array around 200ms after its onset (Luck, 2014; Luck & Ford, 1998).

4.1.3 Current EEG literature for OSM and crowding

There is yet to be a consensus regarding the underlying nature of the processes in OSM and crowding in terms of the underlying neurophysiological processes. For both, various theories have been posited which make specific reference to the nature of the neurocognitive processes which underlie these effects (e.g. Di Lollo et al., 2000; Francis & Cho, 2007; Francis & Hermens, 2002; He et al., 1996; Põder, 2014; Strasburger, 2005; van den Berg et al., 2010). Given this, and given the ubiquity of EEG technology it is somewhat surprising that there are few published electrophysiological studies specifically investigating the underlying neural mechanisms of either OSM or crowding. This is particularly the case with crowding which has a long tradition of psychophysical research going back some 80 years and many hundreds of empirical papers (Levi, 2008); this can be contrasted with the fact that there have been fewer than 10 studies using ERP almost all of which were done in the past 10 years.

4.1.3.1 Electrophysiological investigations of OSM

The investigation into OSM using electrophysiological methods, despite the smaller overall literature, has been more expansive than for crowding. However even here it still includes little more than a handful of studies. These studies to date have predominantly focused on the proposed roles of re-entrant processing and attention in OSM in line with the OSTM, and have tried to identify how it differs from other visual masking phenomena such as noise masking.

Kotsoni and colleagues (2007) constitutes one of the first studies which used ERPs to investigate OSM. They used this technique to examine the proposed role of re-entrant processing in OSM. To recap, the OSTM claims that an iterative, re-entrant process occurs between higher and lower visual areas that is used as a confirmation protocol for target recognition. Within this framework OSM is argued to cause a mismatch and therefore disrupt target recognition (Di Lollo et al., 2000). Kotsoni and colleagues used a standard OSM paradigm whereby the stimulus array consisted of either 1 or 9 circles; the target was identified by the surrounding 4DM. In their first experiment the stimulus array was presented for 13ms; in the second experiment the stimulus array lasted for 40ms. The 4DM offset with the target on half the trials; on the other half of the trials the 4DM trailed the stimulus array for 93ms. Participants were required to identify whether a vertical line bisected the target circle (identifiable by the surrounding 4DM). Kotsoni et al recorded EEG while participants performed this task.

They used the first peak after *N1*, labelled *P2*, as a measure of re-entrant processing. They found that irrespective of the target duration, *P2* amplitude was increased under conditions of masking. This increased *P2* amplitude was not merely related to the change from the stimulus display to the 4DM. If this was the case, the time at which this increased amplitude occurred would have been delayed in the second experiment where the stimulus display duration was extended. It was postulated that this observed increase in *P2* amplitude was a consequence of the mismatch in activity caused by the mask between low level and high level signals during re-entrant processing. Thus it was argued that these findings provided support for the role of re-entrant processing in OSM.

Woodman and Luck (2003) investigated the *N2pc* component in the OSM paradigm as a way of examining the role of attention in OSM. On each trial two possible target locations were presented, one in each visual field; the possible target locations being defined by each having four dots surrounding a display item. Observers had to report whether or not a particular defined target shape (either a square, circle or diamond) was present on a certain trial. The potential target items were presented in a display with 20 other distractor items (all triangles). The designated target that participants had to report the presence or absence of was given at the start of each block.

OSM (defined by having a trailing mask) was compared against noise masking (consisting of a spatially overlapping backward mask with a random pattern of dots). They found OSM to be dissociable from noise masking in terms of its effect on *N2pc* amplitude. When the target was masked by a four dot (OSM) mask the contralateral negativity associated with *N2pc* was still found for targets even under masking conditions, regardless of the fact that target detection was greatly impaired in the masked condition. That is, negative contralateral activity associated with *N2pc* was found 200-375ms after target onset at the same levels in both the unmasked and masked trials.

This finding suggests that masking by OSM had no effect on *N2pc* amplitude. Conversely, when a noise mask was used to interfere with the conscious perception of the target the *N2pc* wave was evident only when the target was not masked. This result suggests that under conditions of OSM, attention can be focused onto the target location prior to masking occurring. Consequently the target was, according to the authors, perhaps represented at some level by the visual system in the first instance and then substituted by the mask percept during re-entrant processing before the task relevant properties of the target could be extracted.

Following on from Woodman and Luck's (2003) study Prime, Pluchino, Eimer, Dell'Acqua and Jolicœur (2011) further examined the *N2pc* component in relation to OSM. Prime and colleagues also extended the investigation to include the effect of OSM at the stage of visual short-term memory (VSTM) encoding. The paradigm used by Prime and colleagues was similar to that used by Woodman and Luck. That is, a target (circle, square or diamond) was presented in both visual fields. The targets were identifiable by the surrounding 4DM. The two targets were presented within a display of twenty distractor triangles, ten in each hemifield. The target type (i.e. circle, square, diamond) was designated at the start of each block. Participants were required to detect whether the designated target was present within the display. As with Woodman and Luck, Prime et al found a consistently large *N2pc* amplitude across correct and incorrect response trials when the target was masked. This further supports the claim that attention is able to be drawn to the target location prior to the target being masked.

In addition to replicating this finding, Prime and colleagues (2011) also observed another deflection in the EEG signal. This was large sustained posterior contralateral negativity (SPCN). SPCN generally occurs at least 300ms post stimulus onset and is associated with visual short term memory (VSTM). SPCN has been shown to increase with increased stimulus numbers and is maximal when the VSTM is at capacity (Jolicœur, Brisson, & Robitaille, 2008). That is, the SPCN is largest when the number of items is equal to or exceeds the postulated capacity of the VSTM store (Vogel & Machizawa, 2004). This component was found only for masked trials when correct responses were made. It was therefore argued that the VSTM experienced an increased load under conditions of masking (Prime et al, 2011). Thus it is possible that the target was initially attended to but was then substituted by the mask due to the failure for the target to be encoded into VSTM in a manner which leads to a stable conscious percept.

Harris et al (2013) recently attempted to identify the time point at which OSM causes a disruption in object processing based on the visual ERP responses to target processing. This study examined the multiple time points associated with both feedforward (low level) processing and feedback (re-entrant) processing. It was found that OSM had no detectable effect on *P1* amplitude; there was no difference in *P1* amplitude under masking conditions. The first effect of OSM was recorded between 130 and 170ms post stimulus on electrodes located over the occipital lobe. This effect was expressed as reduced positivity on incorrect trials. Additionally, a reduction in negative amplitude was observed again for incorrect compared to correct responses. These findings provide further evidence for the role of attention in OSM. These findings also seem to indicate that OSM is not a phenomenon that causes interference during early perceptual processing, rather it seems to emerge from later attention-related processes.

The most recent EEG investigation of OSM conducted to date was by Wynn, Mathis, Ford, Breitmeyer and Green (2013) who explored visual processing deficits with an OSM paradigm recording EEG. Wynn and colleagues examined OSM across a schizophrenia patient group and a control group for signs of differences in visual processing. This study investigated multiple neural correlates of visual processing including the *P1*, *N1* and VAN. The findings showed that the patient group had lower *P1* and *N1* amplitude as well as overall performance compared to the control group irrespective of masking.

Interestingly, amplitude of the *N1* wave correlated with accuracy under masking conditions for the control group (no difference in *N1* was found across masking conditions for the patient group). That is, higher accuracy correlated with higher *N1* amplitude during masking trials for the control group only. This means that when the target was effectively masked, *N1* amplitude was reduced. In addition, the control group exhibited a larger VAN for correct compared to incorrect responses.

These findings therefore suggest that the failure of awareness caused by OSM occurs at least at the stage of target discrimination processing in normal human visual processing. That is, greater attentional processing was visible in the control group (*N1*) which is commonly associated with target discriminability. Furthermore, the clear reduction in VAN produced for incorrect response trials indicates that OSM does indeed effectively prevent awareness of the target.

4.1.3.2 Electrophysiological investigations of crowding

Only a small literature on the electrophysiological correlates of crowding currently exists. To date there are only two full published papers investigating the time course of crowding in terms of ERPs (Chen et al., 2014; Chicherov et al, 2014) along with a handful of published conference abstracts. These full papers will be each discussed in turn.

Chen et al (2014) examined the proposed role of cortical inhibitory interactions between the target and flankers in crowding by focussing on the *C1* component. Chen and colleagues used gratings of different directions as stimuli. The target was presented either in isolation, was closely surrounded by two flankers or appeared with two flankers presented at a far location. The target and distractors were presented in the upper left quadrant of the display (due to the hemispheric restrictions of the *C1*). After a brief interval a single grating would appear in the lower right quadrant of the display. In half the trials participants were asked to attend towards the upper left quadrant; on the other half of trials they were asked to attend towards the lower right quadrant. Participants were required to report on the orientation of the target.

It was revealed that the magnitude of crowding exhibited by the flankers was associated with early inhibitory interactions (pooling) as is most commonly associated with crowding. The ERP analysis showed there was a strong negative *C1* component associated with presence of the flankers surrounding the target. This negative *C1* component was most apparent when the flankers closely surrounded the target. That is, the suppression associated with increased *C1* negativity was strongest under typical conditions of crowding. This suggests that the inhibitory effects of crowding occur within V1. Interestingly, Chen and colleagues also found that attention towards the target tended to modulate the target-flanker interaction as seen in the ERP signal. The suppressive effect of the close distractors was strongest when the target was attended to whereas this suppressive effect diminished under unattended conditions.

Chicherov et al (2014) further examined the electrophysiological mechanisms of crowding based on recent evidence that crowding is caused by grouping of the target and flankers rather than pooling (Manassi, Sayim & Herzog, 2012). Chicherov and colleagues used a vernier crowding paradigm in which the flanking lines varied in size across trials. The vernier target (two abutting lines) was presented within an array of straight lines. The lower of the two abutting lines was offset to either the left or right of the top line. The flanking lines were shorter, longer, or equal to the target. The task was to identify the direction of the lower line in the vernier target. The findings revealed that *P1* amplitude was associated with flanker length irrespective of crowding whereas *N1* amplitude was associated with crowding; *N1* amplitude was smallest under crowding conditions. This supports the claim that *P1* is an early sensory correlate sensitive to low level properties such as stimulus size whereas the reduction in *N1* amplitude reflects a spatial processing impairment associated with target-flanker grouping in crowding.

Given the limited EEG literature on OSM and in particular on crowding, this is clearly an area which is currently under-researched and therefore warrants further study. Certainly no research has yet attempted to compare the effects of OSM and crowding within the same study. Moreover, given the recent findings showing that crowding and OSM interact (as shown in Chapter 3) it is also important to understand the electrophysiological underpinnings of this interaction. This is particularly the case given the claims regarding the proposed locus of crowding and OSM effects within the object processing hierarchy. At present crowding, as a phenomenon that causes processing disruption, is argued to occur earlier in the processing stream than OSM (Breitmeyer, 2014; Breitmeyer, 2015). The repeated production of the inverted U-shaped interaction between OSM and crowding in this series of experiments suggests that perhaps they are more related in the way in which they cause processing disruption.

Given that within the limited existing electrophysiological literature on these phenomena the only ERPs that have been investigated across both OSM and crowding are the *P1* and *N1* and that the *N1* has been found to be modulated by both OSM and crowding it seemed reasonable to use these components as the main focus of the current research. This study aimed to determine the time course in which OSM and crowding affect visual processing. The investigation was interested in exploring whether OSM and crowding are related to early sensory processing or later attentional processing; and whether these two phenomena are dissociable from one another. In particular, this study was interested in finding out at what stage the interaction between OSM and crowding occurs.

4.2 Experiment 11: EEG investigation of OSM and crowding

The results of Experiment 10 directly informed the implementation of this experiment. As such the stimuli were identical to those of Experiment 10a except where stated. The circumferential distance of the virtual circle was 4.75° of visual angle. The number of mask durations used was reduced to two (0, 260). The number of target-flanker distances was reduced to 3: 1°, 5° and 13° of visual angle. These conditions were chosen in the aim of optimising the effects of OSM and crowding individually and also the interaction between them. Furthermore, the number of conditions was reduced to six due to the requirement of EEG recording to have a large number of trials per conditions to produce an adequate SNR for the recorded responses. Having six critical conditions allowed the experimental session to be kept to a reasonable length and allow it to take place in a single extended session. It was expected that this experiment would replicate the inverted U-shaped function of the interaction between OSM and crowding in the behavioural data. It was also expected that the effects of these phenomena would show modulation in the *N1* component. It was expected that both OSM and crowding would cause a reduction in *N1* amplitude. Finally, it was expected that the interaction between OSM and crowding would lead to the greatest reduction in *N1* amplitude.

Method

Participants

Fourteen participants (10 female) took part in the experiment. Participants were recruited from staff and postgraduate students at Oxford Brookes University. All participants were neurologically healthy and reported normal or corrected-to-normal visual acuity.

Design

The experiment had two within-participants independent factors. These were *mask duration* with two levels (0, 260ms) and *target-flanker distance* with three levels (1°, 5° and 13° of visual angle). The dependent variable was *identification performance*, measured by the percentage of correct responses.

Stimuli and procedure

The experiment was conducted in a purpose built EEG suite which was electromagnetically shielded and sound attenuated. Wire gauze covered the surface of the monitor to avoid any inference from the computer. Stimuli were presented on a Dell LCD computer monitor set at a resolution of 1280×960 running at a 100Hz refresh rate. The monitor was controlled by an Intel Core 2 Duo (2.39GHz) PC fitted with an ATI Radeon HD 2400 Pro graphics card. The monitor was viewed at a distance of approximately 100cm. All aspects of stimulus presentation, randomisation and response recording were controlled by E-Prime Version 2.0.8.9 (Psychology Software Tools).

Each trial began with the presentation of a black fixation cross for an average of 1000ms with a jittered onset. The stimulus array was then presented with the four dot mask surrounding the target digit. The stimulus array remained on screen for 40ms and was followed by the trailing mask for either 0 (non-masked, control condition) or 260ms. On non-masked trials, a fixation cross would be displayed for the same duration as the trailing mask. The fixation cross was onscreen throughout the stimulus and mask frames. A red fixation cross display was presented immediately following the mask (and non-mask fixation) array. This red fixation cross alerted the participant to make a response and continued to be displayed until a response was made. Responses were made on a Labtec number pad, pressing a key from 0-9 corresponding to the target identity. Once a key press was made the red fixation cross disappeared and a new trial was instigated. A schematic depiction of the trial sequence is given in Figure 28.

Participants completed 60 practice trials prior to the experimental stage. There were 720 trials, 120 trials for each combination of *masking* and *target-flanker distance*. The trials were presented within 6 distinct blocks. Participants were asked to take a break after each 120 trial interval. Visual response feedback was given during the practice session. No feedback was provided during the testing session.

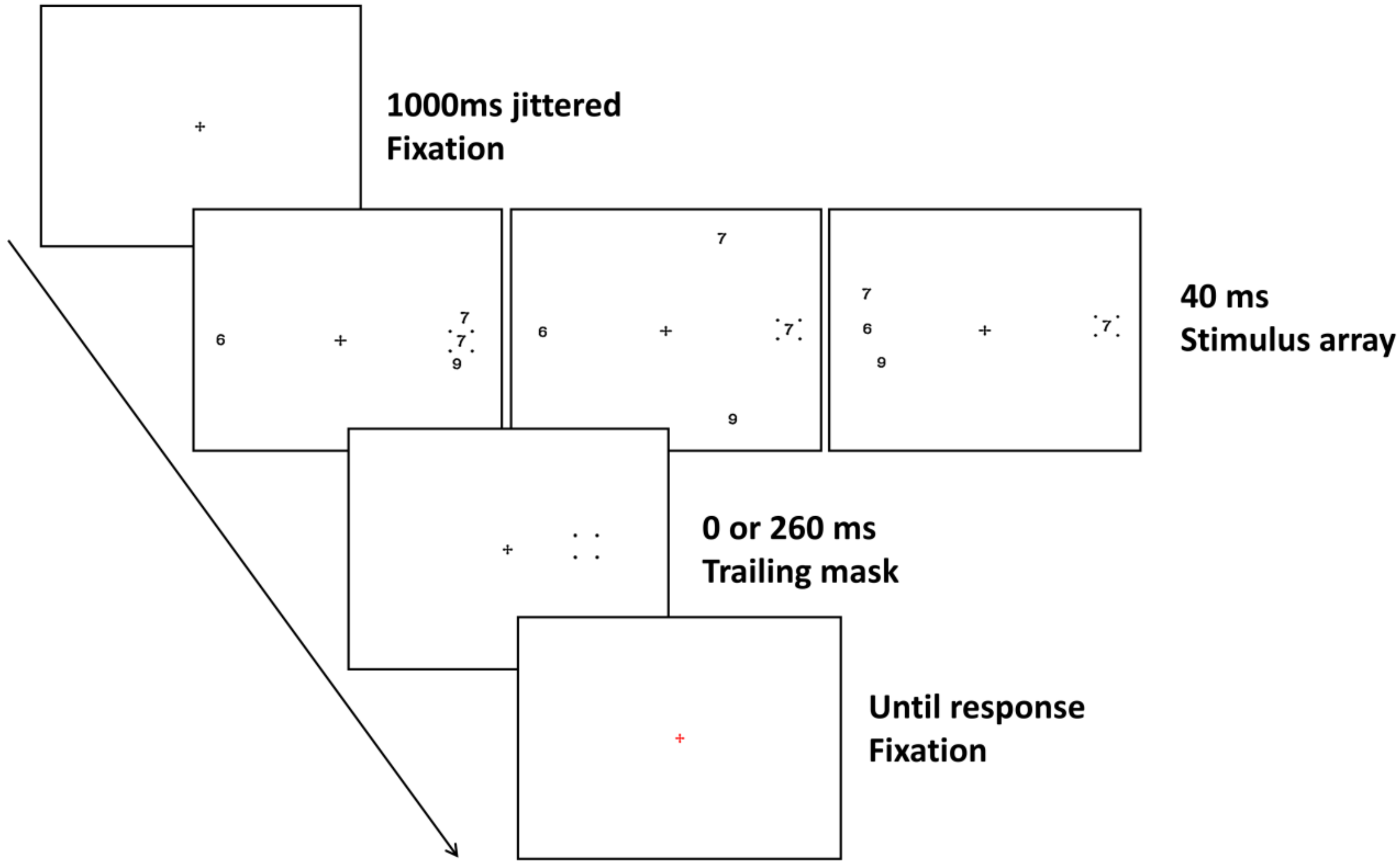

Figure 28| A schematic depiction of the trial sequence in Experiment 11 (electrophysiological investigation). The three stimulus array frames depict examples of trials for (from left to right) a target-flanker distance of 1°, 5° and 13°.

EEG Recording and Data Analysis

EEG data were recording using a 64-channel electrical geodesic net (Electrical Geodesic Inc.; Tucker, 1993). The data were digitised at a rate of 500Hz. Data recording was performed with a hardwire bandpass filter of 0.01Hz to 100Hz. The data were recorded from DC. The online recording was referenced to the vertex electrode (Cz).

Data were offline processed using EEGLab (Delorme & Makeig, 2004). Data were filtered offline with a bandpass rate of 0.1Hz to 30Hz (FIR filter). The data were re-referenced to the average of the left and right mastoids. Stimulus-locked epochs were created for each stimulus condition. Epochs started 100ms before stimulus onset and ended 400ms after stimulus onset.

Artifact rejection was conducted using independent components analysis (ICA). ICA is a statistical technique. Its goal is to find linear projections of the data; that is, it aims to maximise the independence between mutually exclusive components that fall within a specific time window (Delorme & Makeig, 2004; Vigário, Särelä, Jousmiki, Hämäläinen, & Oja, 2000). It has been largely applied to feature extraction and blind source separation (Vigário et al, 2000). This is particularly useful for EEG data processing, specifically when dealing with artifact identification and removal (Vigário et al, 2000). This is due to the different amplitudes that artifacts will exhibit in the EEG signal compared to brain activity (Brunner, Naeem, Leeb, Graimann, & Pfurtscheller, 2007).

ICA decompositions are commonly performed in modern EEG analysis to remove eye blink, eye movement and face muscle movement artifacts which can otherwise corrupt the components of interest (Brunner et al, 2007). Offline ICA decomposition on the EEG data was performed to remove components related to artifacts (such as eye movements) were removed based on topographic distribution, component activation, and their power spectrum (see Appendix A for indicative examples of ICA components obtained from experimental data in the current experiment).

Results

Two participants were excluded from analysis due to irregular EEG data patterns. That is, the data for both participants contained a high level of high frequency noise such as muscle activity.

Behavioural results

The average percent correct responses in each factorial condition of mask duration and crowding are shown in Figure 29(A). These data were analysed using a repeated measures ANOVA with two factors, *mask duration* with two levels (0, 260ms) and *target-flanker distance* with 3 levels (1°, 5° and 13° visual angle).

There were significant main effects of *mask duration*, $F(1, 11)=19.67$, $MS^{error}=20.01$, $p=.001$, $\eta_p^2=.64$, and *target-flanker distance* $F(2, 22)=23.75$, $MS^{error}=94.12$, $p<.001$, $\eta_p^2=.68$ (using Greenhouse-Geisser correction). Importantly, a significant interaction was also found between *mask duration* and *target-flanker distance* $F(2, 22)=4.89$, $MS^{error}=9.77$, $p=.017$, $\eta_p^2=.31$. Examination of Figure 29 indicates that the interaction resulted from the fact that OSM (as indexed by mask duration) was most effective at the medium-target flanker distance.

Simple effects t-tests were conducted and revealed that crowding was strongest at the closest target-flanker distance. There was a significant difference in performance between a target-flanker distance of 1° and 5° ($t[11]=5.31$, $p<.001$) and between a target-flanker distance of 1° and 13° ($t[11]=5.33$, $p<.001$). There was no significant difference in performance between a target-flanker distance of 5° and 13° however ($t([11]=1.43$, $p=.181$) indicating that the target was beyond the range of crowding at a distance of 5° when unmasked.

Further simple effects t-tests revealed that OSM has little effect on crowding at the closest target-flanker distance ($t[11]=1.00$, $p=.338$). OSM did increase the performance impairment at the larger target-flanker distance however. There was a significant difference is performance between unmasked and masked conditions at a distance of 5° (t[11]=4.13, p=.002) and a distance of 13° (t[11]=4.34, p=.001). Simple effects t-tests also revealed that there were differences in performance across the masked-crowded conditions. There was a significant difference in performance between a target-flanker distance of 1° and 5° (t[11]=4.33, p=.001), 1° and 13° (t[11]=4.32, p=.001) and 5° and 13° (t[11]=2.65, p=.022) at a mask duration of 260ms.

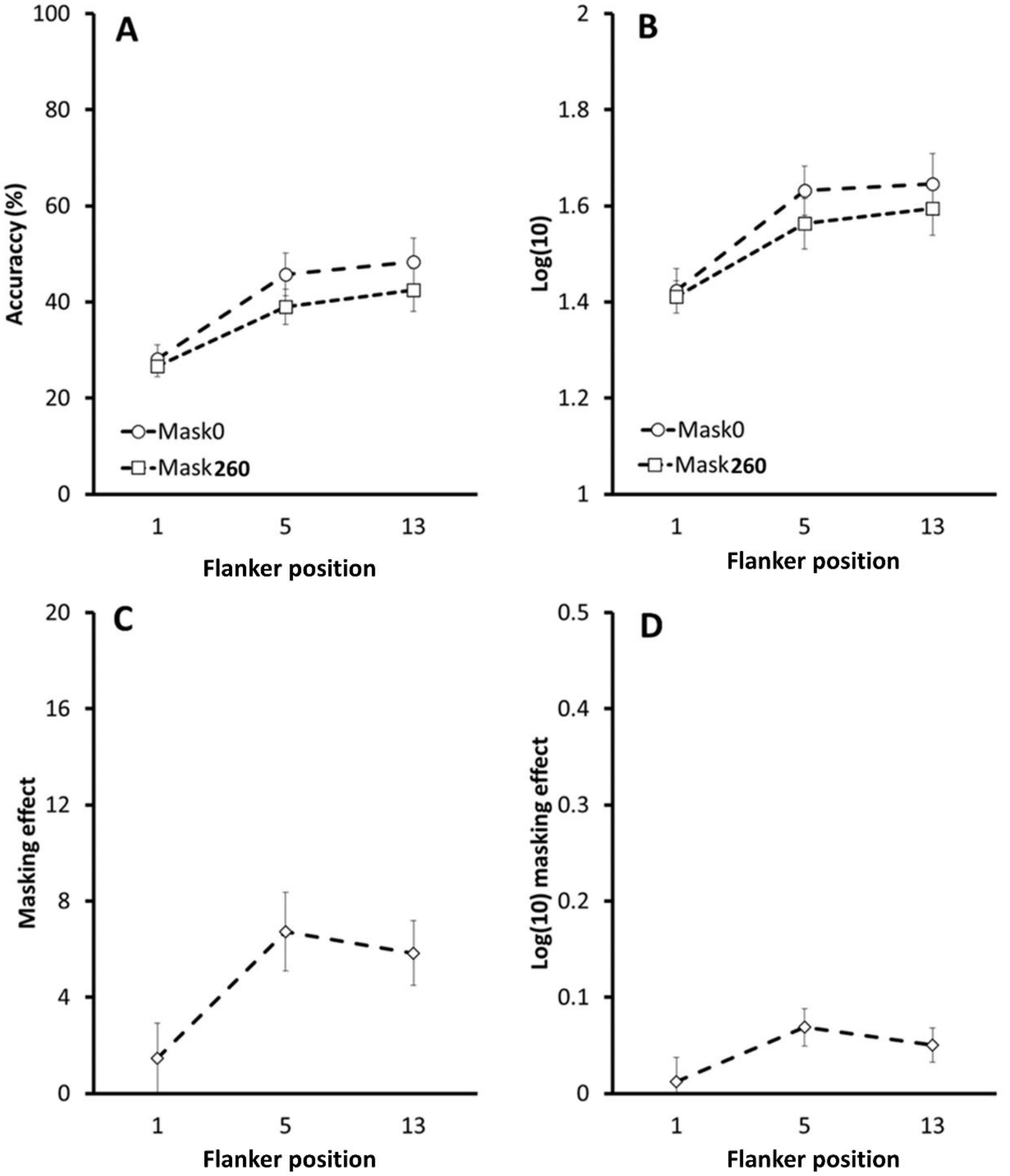

Figure 29| Performance in Experiment 11 (electrophysiological examination). The figure shows accuracy (% correct; plate A) and transformed accuracy (Log10; plate B) for the three target-flanker distances (1°, 5°, 13°) by each of the two mask duration conditions (0, 260ms). Plate C shows the masking effect (difference between 0ms and 260ms mask duration) and Plate D shows the transformed masking effect across the three target-flanker proximities. Error bars represent +/-1 standard error of the mean.

ERP Analysis

Based on previous literature the *P1* (70-90ms) and *N1* (90-140ms) components were the focus of the ERP analysis. VAN (200-300ms) was also examined in the data. Initial inspection of the ERP data made it clear that there was no visible positive peak within the expected window for *P1*. A positive peak was found between 45 and 75ms however. This peak was classified as the *visual P50*. ERP analysis was conducted at individual electrodes. The left hemispheric grouping included electrodes E30, E31, E32, E33 and E35. The right hemispheric grouping included electrodes E38, E39, E40, E43 and E44. Each of these electrodes was also investigated independently.

The hemispheric groupings investigated the mean amplitude of the whole dataset (see Figure 32) and for correct vs. incorrect trials (see Figure 33) rather than the peak as the peak across participants was relatively wide. Analysis was conducted on the comparison between correct and incorrect trials because the study aimed to investigate the neural correlates of conscious perception. As such, it seems reasonable to expect that correct trials would represent conscious perception of the target whereas incorrect trials would not, particularly as this is a well-established method for determining VAN in the literature (Koivisto et al., 2007; Koivisto & Revonsuo, 2003; Koivisto & Revonsuo, 2010). Thus, there was an expectation that these types of trials would show differences in their neural correlates. In particular, it was expected that the VAN would be seen in the difference between correct and incorrect trials. The same method of analysis was followed for the individual electrodes both for the group electrode (see Figure 34) and individual electrode analysis (see Figure 35). Discussion of these components will now be given in turn.

P50

P50 Group analysis

The mean positive amplitude in the 45-75ms time window for each posterior hemispheric grouping was analysed using a repeated measures ANOVA with three factors, hemisphere with two levels (left, right), mask *duration* with two levels (0, 260ms) and *target-flanker distance* with 3 levels (1˚, 5˚, or 13˚ visual angle). There was no significant main effect of hemisphere, $F(1, 11)=0.13$, $MS_{error}=1.48$, $p=.727$, masking, $F(1, 11)=0.05$, $MS_{error}=0.09$, $p=.821$ or crowding, $F(2, 22)=2.06$, $MS_{error}=0.18$, $p=.151$, on amplitude. There was no significant interaction between hemisphere and OSM, $F(2, 22)=1.35$, $MS_{error}=0.07$, $p=.271$ or hemisphere and crowding, $F(2, 22)=.25$, $MS_{error}=0.07$, $p=.758$. There was also no significant interaction between crowding and OSM, $F(2, 22)=0.44$, $MS_{error}=0.31$, $p=.649$ or a three way interaction between hemisphere, masking and crowding, $F(2, 22)=0.40$, $MS_{error}=0.07$, $p=.678$. This can be seen in Figure 30 in which the scalp distribution of the *P50* effect is presented. Here it is clear that the posterior positivity related to the *P50* is equivalent across all the experimental conditions.

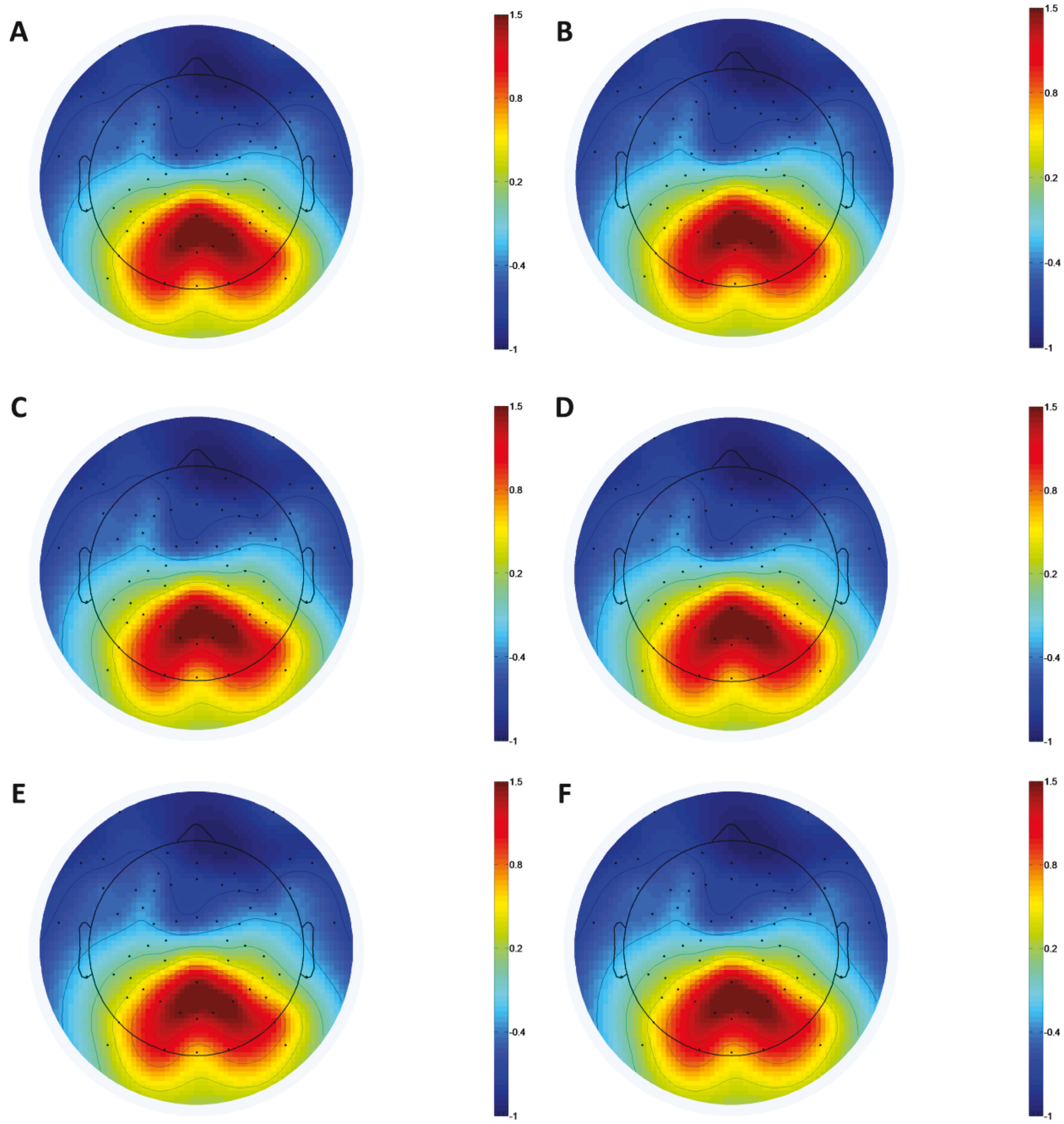

Figure 30| Topographic scalp maps for the *P50* component at the 58ms peak for the unmasked-crowded (plate A), unmasked-medium crowding (plate B), unmasked-uncrowded (plate C), masked-crowded (plate D), masked-medium crowding (plate E) and masked-uncrowded (plate F) conditions respectively.

P50 Correct vs. Incorrect analysis

The mean positive amplitude grouping in the 45-75ms time window for each hemispheric grouping was analysed separately for correct and incorrect trials using a repeated measures ANOVA with four factors. These factors were *hemisphere* with two levels (left, right), *performance* with two levels (correct, incorrect), *mask duration* with two levels (0, 260ms) and *target-flanker distance* with 3 levels (1˚, 5˚ and 13˚ of visual angle). There was no significant effect of hemisphere, $F(1,11)=0.02$, $MS^{error}=4.82$, $p=.889$, *correct vs. incorrect performance*, $F(1,11)=1.45$, $MS^{error}=0.64$, $p=.253$, *masking*, $F(1,11)=0.36$, $MS^{error}=0.24$, $p=.562$ or *crowding*, $F(2,22)=0.72$, $MS^{error}=0.53$, $p=.497$ (see Figure 33). There was no significant interaction between *hemisphere* and *OSM,* $F(1, 11)=0.01$, $MS^{error}=0.18$, $p=.917$ or *performance* and *OSM*, $F(1, 11)=0.12$ $MS^{error}=0.28$, $p=.736$. There was also no significant interaction between *hemisphere* and *crowding*, $F(2, 22)=1.14$, $MS_{error}=0.09$, $p=.339$, *performance and crowding*, $F(2, 22)=1.36$, $MS_{error}=0.68$, $p=.387$, or *crowding* and *OSM*, $F(2, 22)=0.24$, $MS^{error}=0.19$, $p=.791$. There was also no significant three-way interaction between *hemisphere*, *performance* and *OSM*, $F(1, 11)=0.89$, $MS^{error}=0.12$, $p=.366$, *performance, OSM and crowding,* $F(2, 22)=1.91$, $MS^{error}=0.39$, $p=.171$ or *hemisphere*, *performance* and *crowding*, $F(2, 22)=0.21$, $MS^{error}=0.19$, $p=.813$. There was also no four-way interaction between hemisphere, response, OSM and crowding, $F(1, 11)=2.19$, $MS^{error}=0.16$, $p=.136$.

P50 Analysis by individual electrodes

The mean positive amplitude (for the 45-75ms time window) for each individual electrode was analysed using a repeated measures ANOVA with two factors, *mask duration* with two levels (0, 260ms) and *target-flanker distance* with three levels (1˚, 5˚ and 13˚ visual angle). There were no significant main effects for OSM or crowding. There was also no significant interaction between OSM and crowding (see Appendix 1, Table 1).

P50 Individual electrode Correct vs. Incorrect analysis

The mean positive amplitude (for the 45-75ms time window) of correct and incorrect trials for each individual electrode was analysed using a repeated measures ANOVA with three factors, *performance* with two levels (correct, incorrect), *mask duration* with two levels (0, 260ms) and *target-flanker distance* with three levels (1˚, 5˚ and 13˚ visual angle). There were no significant main effects of, correct vs. incorrect performance, OSM or crowding. There were also no significant interactions between performance, OSM and crowding (see Appendix 2, Table 2).

N1

N1 Group analysis

The mean negative amplitude (for the 90-140ms time window) associated with *N1* for each posterior hemispheric grouping was analysed using a repeated measures ANOVA with three factors, *hemisphere* with two levels (left, right), *mask duration* with two levels (0, 260ms) and *target-flanker distance* with 3 levels (1˚, 5˚ and 13˚ visual angle). There was no significant main effect of *hemisphere,* $F(1, 11)=1.56$, $MS^{error}=13.26$, $p=.238$, *masking*, $F(1, 11)=0.09$, $MS^{error}=0.09$, $p=.767$ or crowding, $F(2, 22)=1.40$, $MS^{error}=0.16$, $p=.267$ (see Figure 32). There was no significant interaction between *hemisphere* and *masking,* $F(1, 11)=0.74$, $MS^{error}=.07$, $p=.407$, *hemisphere* and *crowding*, $F(2, 22)=0.76$, $MS^{error}=.06$, $p=.479$, or *OSM* and *crowding*, $F(2, 22)=0.48$, $MS^{error}=.14$, $p=.623$. There was also no significant three-way interaction between *hemisphere, masking* and *crowding,* $F(2, 22)=.62$, $MS^{error}=.10$, $p=.545$. This can be seen in Figure 31 in which the scalp distribution of the N1 effect is presented. Here it is clear that the posterior negativity which characterises the N1 is equivalent across all the experimental conditions.

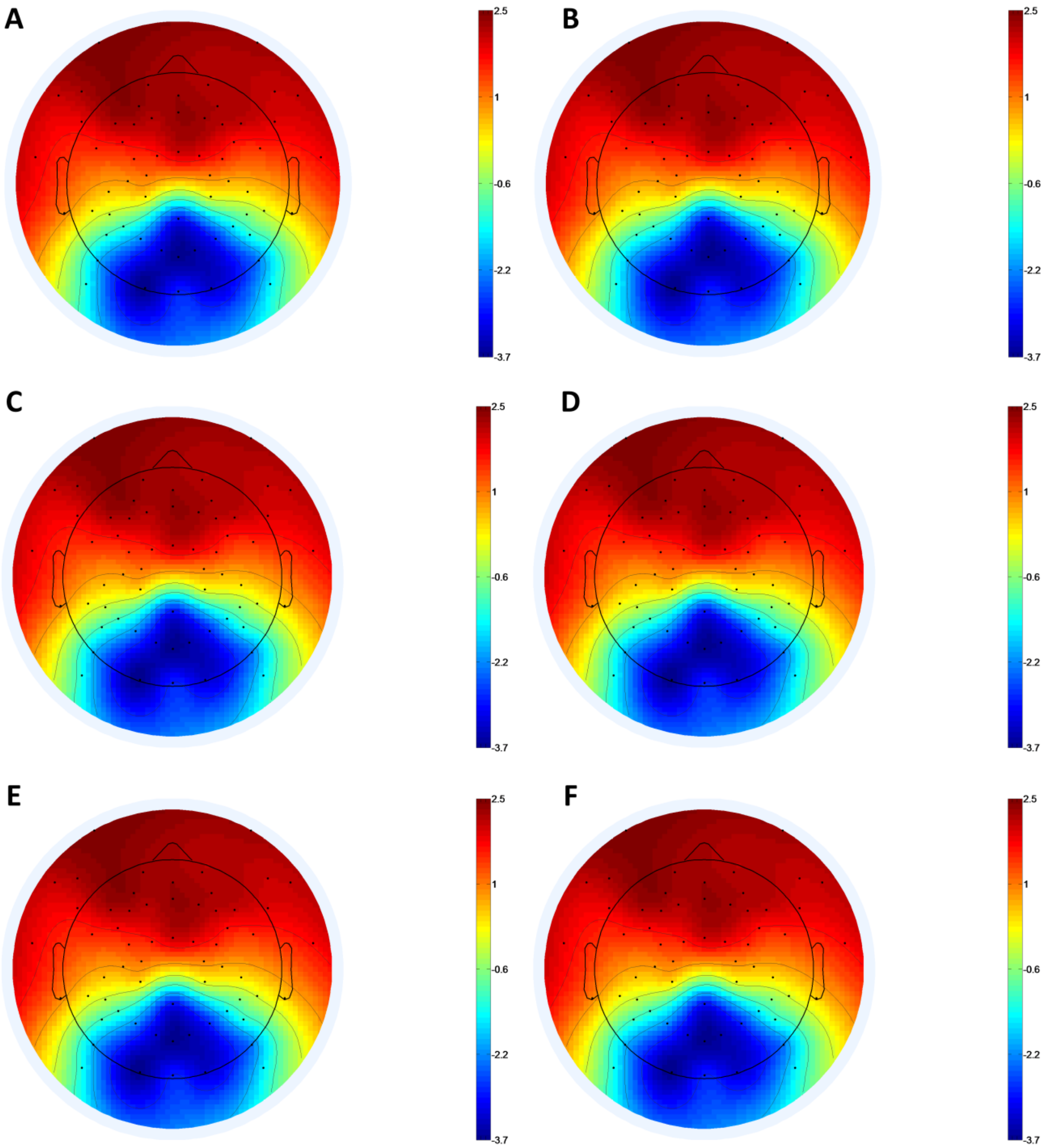

Figure 31| Topographic scalp maps for the *N1* component at the 105ms peak for the unmasked-crowded (plate A), unmasked-medium crowding (plate B), unmasked-uncrowded (plate C), masked-crowded (plate D), masked-medium crowding (plate E) and masked-uncrowded (plate F) conditions respectively.

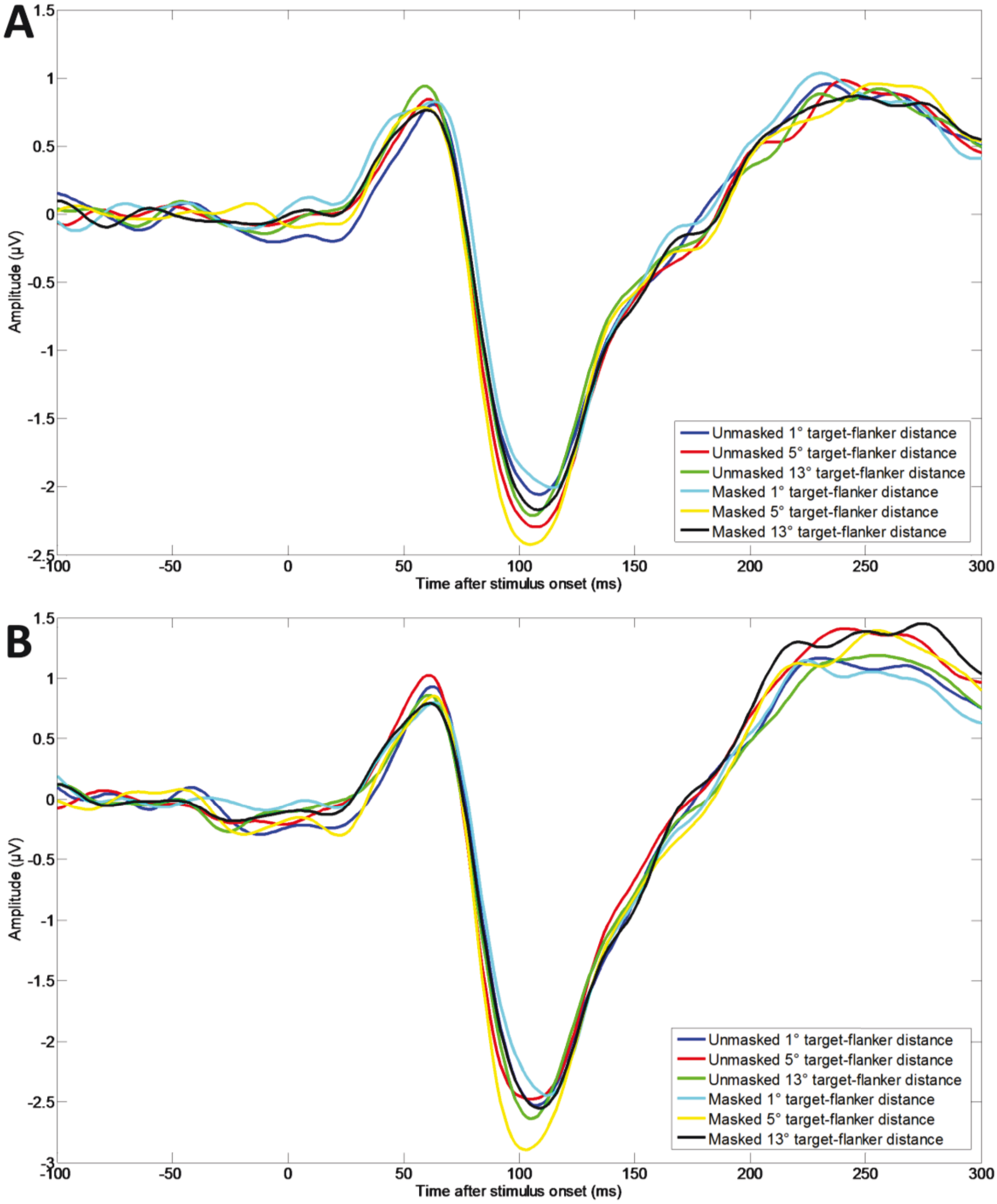

Figure 32| Grand average waveforms representing the left (plate A) and right (plate B) electrode groups for the three target-flanker proximities (1°, 5°, 13°) by each of the two mask duration conditions (0, 260ms). Waveforms are baseline corrected to -100ms.

N1 Correct vs. Incorrect trials analysis

The mean negative amplitude associated with *N1* (90-140ms) for each posterior hemispheric grouping was analysed using a repeated measures ANOVA with four factors, *hemisphere* with two levels (left, right), *correct vs. incorrect performance* with two levels (correct, incorrect), *mask duration* with two levels (0, 260ms) and *target-flanker distance* with three levels (1˚, 5˚ and 13˚ visual angle). There was no significant main effect of *hemisphere,* $F(1, 11)=0.31$, $MS^{error}=27.56$, $p=.588$, *performance*, $F(1, 11)=1.62$, $MS^{error}=0.72$, $p=.229$ or *masking*, $F(1, 11)=0.47$, $MS^{error}=0.61$, $p=.506$. There was however a significant main effect of *crowding*, $F(2, 22)=5.42$, $MS^{error}=0.25$, $p=.012$, $\eta_p^2=.33$. This effect of crowding is the result of increased negative amplitude at the medium target-flanker distance. There was no significant interaction between *hemisphere* and *performance,* $F(1, 11)=0.08$, $MS^{error}=0.07$, $p=.787$, *hemisphere* and *masking*, $F(1, 11)=1.02$, $MS^{error}=0.05$, $p=.335$ or *performance* and *masking*, $F(1, 11)=0.84$, $MS^{error}=0.09$, $p=.380$. There was also no significant interaction between *hemisphere* and *crowding,* $F(2, 22)=0.72$, $MS^{error}=0.16$, $p=.499$, *performance* and *crowding*, $F(2, 22)=2.76$, $MS^{error}=0.33$, $p=.085$ or *masking* and *crowding*, $F(2, 22)=1.70$, $MS^{error}=0.32$, $p=.207$. There was no significant three-way interaction between *hemisphere, performance* and *masking*, $F(1, 11)=.01$, $MS^{error}=0.92$, $p=.947$ or *hemisphere, performance* and *crowding,* $F(2, 22)=2.69$, $MS^{error}=0.08$, $p=.091$. There was also no significant three-way interaction between *performance, crowding* and *OSM*, $F(2, 22)=1.02$, $MS^{error}=0.46$, $p=.376$ or *hemisphere, OSM* and *crowding*, $F(2, 22)=1.23$, $MS^{error}=0.18$, $p=.312$. There was also no significant four-way interaction between these variables, $F(2, 22)=3.10$, $MS^{error}=.09$, $p=.065$ (see Figure 34).

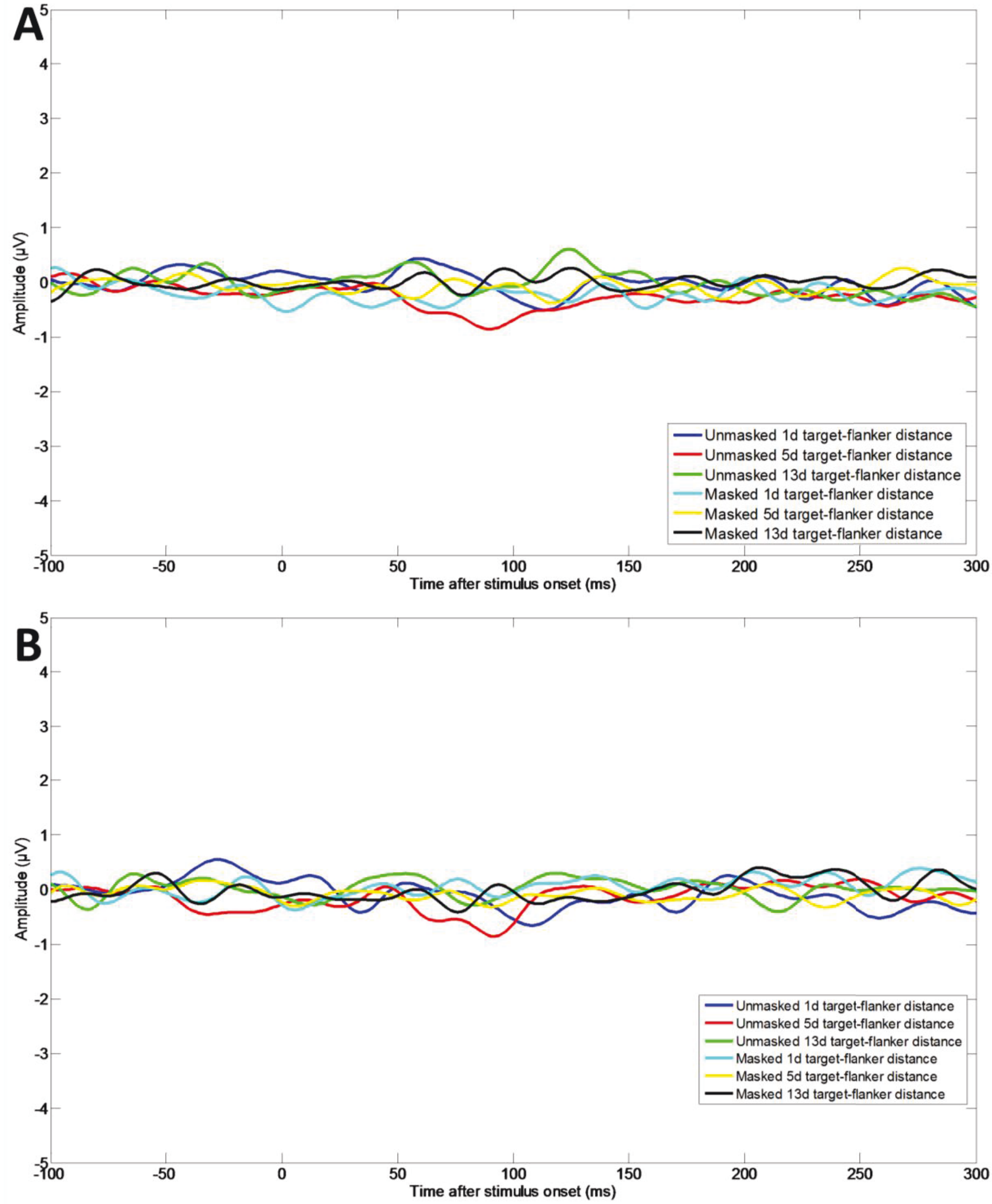

Figure 33| Difference waveforms between correct and incorrect responses representing the left (plate A) and right (plate B) electrode groups for the three target-flanker proximities (1°, 5°, 13°) by each of the two mask duration conditions (0, 260ms).

N1 Analysis by individual electrodes

The mean negative amplitude (90-140ms) for each individual electrode was analysed using a repeated measures ANOVA with two factors, *mask duration* with two levels (0, 260ms) and *target-flanker distance* with 3 levels (1˚, 5˚ and 13˚ visual angle). No significant main effects were revealed for *masking*. There were also no significant interactions between *masking* and *crowding* (see Appendix 2, Table 3). There was however a significant main effect of *crowding* at electrode E32 ($F[2, 22]=5.57$, $MS^{error}=0.04$, $p=.011$, $\eta_p^2=.34$), E33 ($F[2, 22]=4.91$, $MS^{error}=.12$, $p=.017$, $\eta_p^2=.31$) and E35 ($F[2, 22]=6.95$, $MS^{error}=0.10$, $p=.005$, $\eta_p^2=.39$). This effect of crowding relates to increased negativity at the medium target-flanker distance during both masked and unmasked trials.

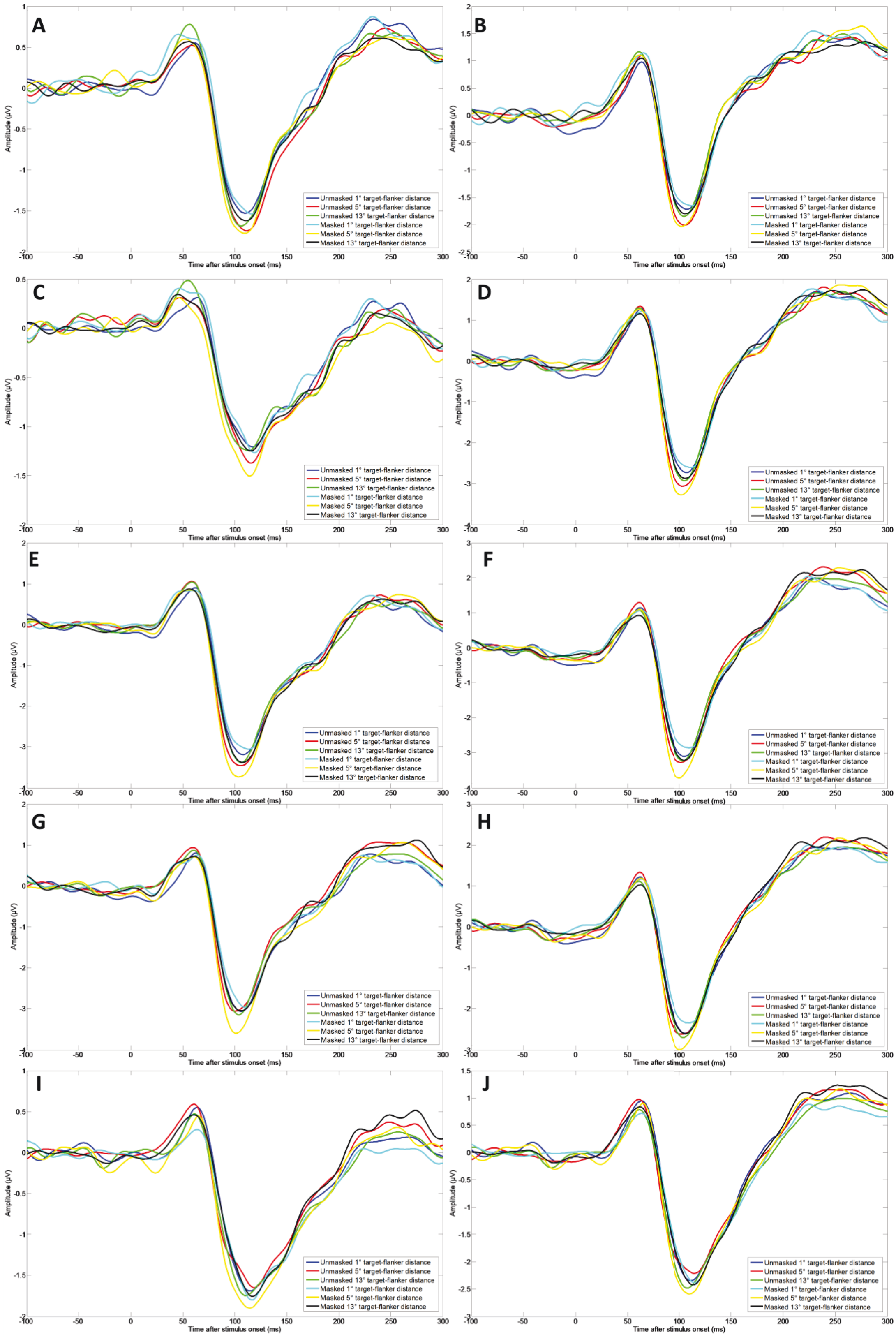

Figure 34| Grand average waveforms for each electrode: E30 (plate A), E31 (plate B), E32 (plate C), E33 (plate D), E35 (plate E), E38 (plate F), E39 (plate G), E40 (plate H), E43 (plate I) and E44 (plate J) for the three target-flanker proximities (1°, 5°, 13°) by each of the two mask duration conditions (0,260ms).

N1 Individual electrode Correct Vs. Incorrect analysis

The mean negative amplitude associated with *N1* for each individual electrode was analysed using a repeated measures ANOVA with three factors, *performance* with two levels (correct, incorrect), *mask duration* with two levels (0,260ms) and *target-flanker distance* with three levels (1˚, 5˚ and 13˚ visual angle). There were no significant effects of correct compared to incorrect *performance* or *masking*. There was also no significant interaction between *performance* and *OSM* (see Appendix 2, Table 4). There were however significant main effects of *crowding* with the E30 ($F[2,22]=4.43$, $MS^{error}=0.19$, $p=.024$, $\eta_p^2=.29$), E31 ($F[2,22]=4.98$, $MS^{error}=0.34$, $p=.016$, $\eta_p^2=.31$), E32 ($F[2,22]=4.25$, $MS^{error}=0.16$, $p=.027$, $\eta_p^2=.28$) and E33 electrodes ($F[2,22]=6.01$, $MS^{error}=0.25$, $p=.008$, $\eta_p^2=.35$). The E35 electrode also revealed a significant main effect of *crowding* ($F[2, 22]=10.26$, $MS^{error}=0.19$, $p=.001$, $\eta_p^2=.48$). There were also significant interactions between *performance* and *crowding* with the E30 ($F[2, 22]=3.63$, $MS^{error}=0.29$, $p=.043$, $\eta_p^2=.25$) and E31 electrodes ($F[2, 22]=4.59$, $MS^{error}=0.29$, $p=.022$, $\eta_p^2=.30$). Finally, the E44 electrode revealed a significant three-way interaction between *performance, OSM* and *crowding* ($F[2, 22]=8.17$, $MS_{error}=0.06$, $p=.002$, $\eta_p^2=.43$). These significant effects relate to the increased negativity that occurred for a medium target-flanker distance.

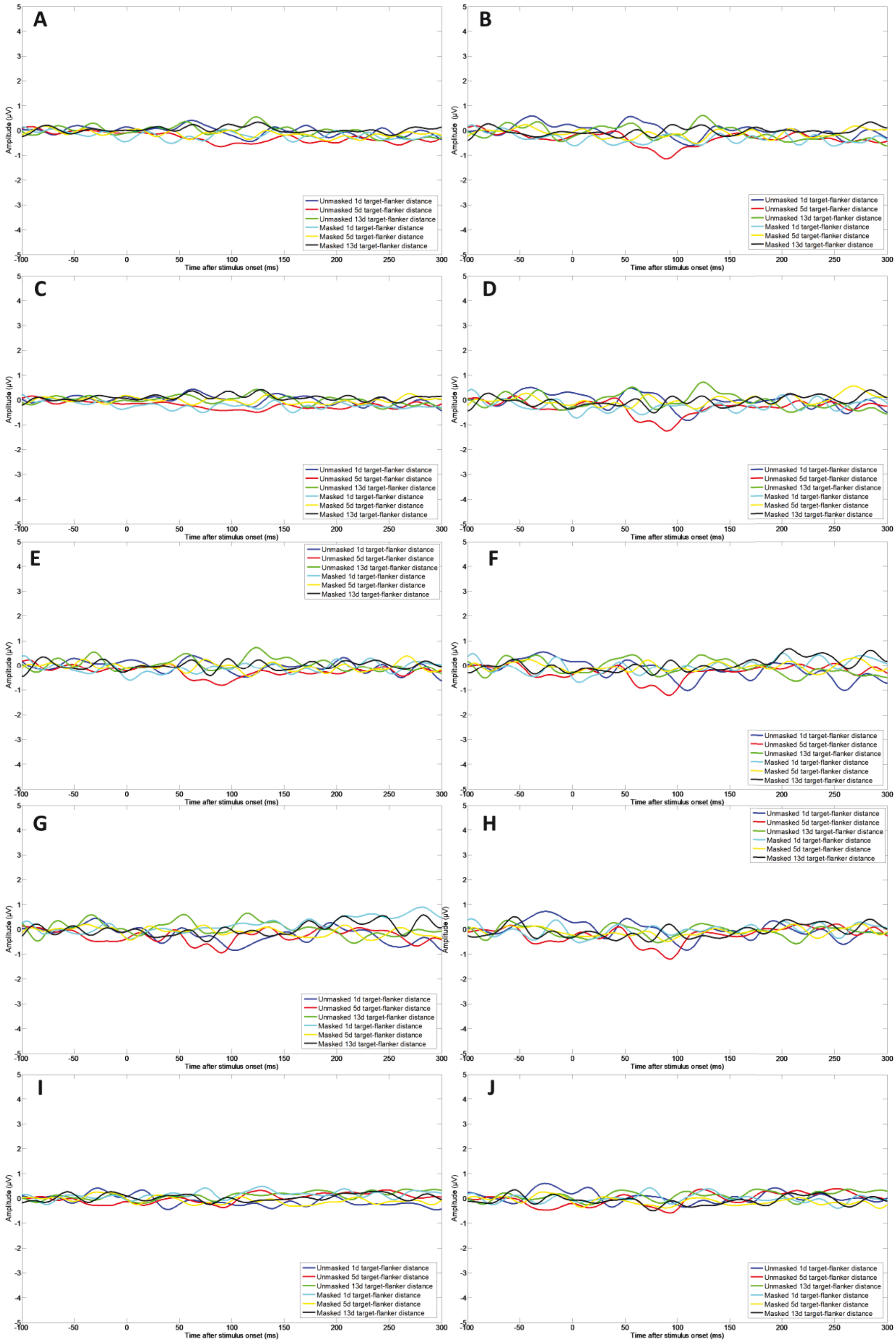

Figure 35| Difference waveforms between correct and incorrect trials for each electrode: E30 (plate A), E31 (plate B), E32 (plate C), E33 (plate D), E35 (plate E), E38 (plate F), E39 (plate G), E40 (plate H), E43 (plate I) and E44 (plate J) for the three target-flanker proximities (1°, 5°, 13°) by each of the two mask duration conditions (0,260ms).

VAN analysis

The mean negative amplitude associated with *VAN* (200-300ms) for each posterior hemispheric grouping was analysed. *VAN* is an ERP based on the difference in amplitude between correct and incorrect responses. This analysis used a repeated measures ANOVA with two factors, *mask duration* with two levels (0,260ms) and *target-flanker distance* with 3 levels (1°, 5° and 13° visual angle). The left posterior grouping revealed no significant main effect of *masking*, $F(1, 11)=1.57$, $MS^{error}=0.37$, $p=.237$ or *crowding*, $F(2, 22)=0.10$, $MS^{error}=0.45$, $p=.903$. There was no significant interaction between *OSM* and *crowding*, $F(2, 22)=0.63$, $MS^{error}=0.43$, $p=.544$. The right posterior grouping revealed no significant main effect of *masking*, $F(1, 11)=2.18$, $MS^{error}=0.36$, $p=.168$ or *crowding*, $F(2, 22)=0.44$, $MS^{error}=0.21$, $p=.652$. There was no significant interaction between *OSM* and *crowding*, $F(2, 22)=0.94$, $MS^{error}=0.58$, $p=.407$.

4.3 Discussion

Experiment 11 was conducted for two main reasons. Firstly, this experiment aimed to establish at what stage the failure of awareness caused by both OSM and crowding individually occurs. Secondly, the aim was to understand the underlying processing stage at which the interaction between OSM and crowding occurs. It was expected that the behavioural results would be consistent with those reported in Chapter 3. Specifically, an interaction was expected between OSM and crowding exhibiting as an inverted U-shaped function. That is, the effect of OSM was expected to be strongest at the medium target-flanker distance. In terms of the electrophysiological data, it was predicted that a robust *P1* component would be found across all conditions i.e. neither OSM nor crowding would impact *P1* amplitude. It was expected that amplitude modulation would occur at the point of the *N1* component. That is, both OSM and crowding were expected to cause an inhibition of *N1* amplitude. Furthermore, it was expected that the interaction between OSM and crowding would be expressed as a greater attenuation of *N1* than that produced by OSM or crowding individually.

The behavioural results of Experiment 11 replicated the existence of an interaction between OSM and crowding. This interaction was again expressed as an inverted U-shaped function with OSM strongest at the medium target-flanker distance. The electrophysiological data examined early positive and negative ERPs associated with visual processing. There was no evidence of the emergence of a *P1* found within the expected time window (70-90ms); it is unclear why this would be the case. There was however early positivity found in the 50ms region which was described as being a visual *P50*. Analysis was therefore conducted on visual *P50,* instead of *P1*. The data revealed no significant effect of any of the variables in the experiment: OSM, crowding or the OSM×crowding interaction on this *visual P50* component.

The *N1* component was also examined for differences in amplitude associated with crowding and OSM. As with the *visual P50* no significant amplitude changes associated with OSM or with the interaction between OSM and crowding were found. There were however significant effects of target-flanker distance on *N1* amplitude on a subset of electrodes. This effect was associated with increased negativity at the medium target-flanker distance in both the unmasked and masked conditions. To specify, negative amplitude was almost equivalent at the small and large target-flanker distances with a substantial increase in the negative amplitude at the medium target-flanker distance. Thus, contrary to the prediction of Experiment 11, the small target-flanker distance did not cause a substantial reduction in *N1* amplitude in the standard crowding condition. The analysis of VAN revealed no significant changes in amplitude associated with OSM, crowding, or the interaction between the phenomena.

The behavioural results of Experiment 11 provide only partial support for those of Chapter 3. That is, the findings replicated an inverted U-shaped function of the interaction between OSM and crowding. The effect showed that OSM was strongest at the medium target-flanker distance with a minimal effect of OSM at the small target-flanker distance. In contrast to Experiments 9 and 10 however, the masking effect remained relatively small even at the medium target-flanker distance (the amplitude of OSM did not exceed a 7% reduction in performance). Further to this, there was not a substantial reduction in the masking effect at the large target-flanker distance. The previous experiments showed what could arguably be classified as a release from OSM at the large target-flanker distances. This was expressed as increased performance that was comparable across both the unmasked and masked conditions. This was not found to the same extent in Experiment 11. It is plausible therefore that the restricted conditions of target-flanker distance used in Experiment 11 did not optimise the assessment of the interaction between OSM and crowding.

When evaluating the electrophysiological data, the significant effects of crowding on amplitude presented must be met with caution. The significant effect of crowding found in the *N1* related amplitude was associated with increased negativity at the medium target-flanker distance across both masked and unmasked conditions. What was expected from crowding is that it would cause a reduction in negative amplitude at the small target-flanker distance. Nevertheless, if the amplitude changes at the medium target-flanker distance were related to crowding it would be expected that a reduction in negativity would occur, as has been found previously (Chicherov et al., 2014), given the possible reduction in attentional allocation to the target. This is in direct contrast to the changes in amplitude found in Experiment 11 however.

As such, there is no evidence from the current experiment or the crowding literature to suggest that these changes in amplitude relate in any way to the phenomenon of crowding per se. That is, a fundamental component of crowding is that it impairs processing when the target is closely flanked by surrounding distractors (Levi, 2008). As such, the fact that the amplitude changes were at the medium target-flanker distance seems to have little relation to the crowding effect itself. Rather, one explanation for this effect is that the increase in amplitude at the medium target-flanker distance could be related to the display configuration. There is evidence of *N1* being associated with the facilitation of attentional focusing (Eimer, 1993). For example, increased *N1* has been found for attended compared to unattended stimuli (Clark & Hillyard, 1996) and during increased discriminative processing (Vogel & Luck, 2000).

Consequently, under the conditions of Experiment 11, it is possible that the different target-flanker distances could produce different modulations of this *N1* facilitation. For instance, at the small target-flanker distance, three of the stimuli (the centre one of which was the target) were presented at one location on the screen with the fourth distractor being presented opposite them. Likewise, with the large target-flanker distance three distractors were presented at one location on the screen with the target presented in isolation opposite them. At the medium target-flanker distance however, the stimuli were relatively evenly spread around the circumferential display. It is possible therefore that the different display configuration at the medium target-flanker distance resulted somehow in greater attentional deployment and/or increased discriminative processing which may occur under these conditions.

Importantly, this effect at the medium target-flanker distance was found across unmasked and masked conditions. Thus, it is difficult to relate this effect to the behavioural results of the interaction between crowding and OSM. It could indeed be that the difference in *N1* modulation found is related to attentional deployment but not in a way which is related to the effect of OSM on crowding. Ultimately therefore, there is little that can be concluded from this effect about the effect of OSM on crowding and as such, caution is required in not over interpreting these aspects of the results.

These electrophysiological findings are in contrast to some of the previous literature presented in section 4.3. The rationale for Experiment 11 came from the fact that modulation of *N1* has been reported for both OSM and crowding (e.g. Chicherov et al., 2014; Wynn et al., 2013). Chicherov and colleagues found that *N1* amplitude was heavily attenuated when the target was crowded (i.e. when the target was closely flanked by surrounding distractors). Equally, Wynn and colleagues found increased *N1* amplitude was associated with correct responding under masking conditions. That is, when the mask resulted in a lack of awareness of the target *N1* amplitude was substantially reduced.

It is worth noting however that there are substantial differences between these studies and the current study. In particular, the study conducted by Chicherov et al (2014) was markedly different from Experiment 11. Chicherov et al presented a vernier crowding experiment meaning the stimuli were simple lines that were presented in a row in contrast to the more complex stimulus display used in Experiment 11. Furthermore, there was no form of masking used in their experiment. The study conducted by Wynn and colleagues (2013) used an OSM paradigm and as such was potentially more comparable to Experiment 11. Nevertheless, the design of this study also presented with numerous differences. The primary interest of Wynn and colleagues was the differential effect of OSM between a control population and a schizophrenia patient population. Furthermore, OSM was investigated through SOAs. That is, the target and 4DM did not onset together but rather, after varied offset times of the target the mask would be presented. It is also worth noting that when reviewing the results of Wynn and colleagues, the significant results found were for incorrect compared to correct trials in relation to the participants' accuracy data. Thus, this would suggest that they were unable to produce any consistent and substantive OSM effects on the full dataset. As such, it is perhaps not surprising that the previous studies presented with such differing results to Experiment 11.

Nevertheless, the findings of the current experiment suggest that perhaps early visual processing of the target is unaffected by either crowding or OSM, at least under the conditions of the paradigm presented here. Rather, it would suggest that perhaps both phenomena, and the interaction that occurs between them, occur at a later stage of object processing than was assessed in Experiment 11. As such, these results would suggest that the interaction between OSM and crowding does not occur as the consequence of low-level pooling (Wilkinson et al., 1997) of the target and flanker information at this medium target-flanker distance. Rather, the lack of an effect on either *P1* or *N1* amplitude caused by the interaction would suggest it is in fact a later occurring restriction of awareness. Arguably therefore this interaction could occur during re-entrant processing and/or require more selective attentional processing. However, it could also be that the paradigm used in this experiment simply was not sensitive enough to the underlying processing of this interaction between crowding and OSM. This is particularly likely given the reduced masking effect found in this experiment compared to those in Chapter 3.

Unfortunately therefore, the results of this study do not inform very much about either crowding or OSM. They were not able to directly elucidate about the level of processing impairment for either phenomena individually or the interaction between them. As such, there was no evidence of whether crowding and OSM occur at distinct locations within the object processing hierarchy and whether their interaction is more in line with crowding or OSM processes in terms of the stage at which it occurs. However it is conceivable that these phenomena are not low level processing impairments as the early visual related components used in Experiment 11 were unaffected by either phenomena. That is, from the results of this experiment it would suggest that the *P1* and *N1* components are perhaps too early occurring to assess the stage at which these phenomena affect visual awareness, and the stage at which they interact. It could be that examining sustained responses to the target rather than the initial onset evoked responses to the target would be a better way of exploring these phenomena. The ways in which this could be assessed in future will be discussed in Chapter 5.

4.4 Chapter Summary

The aim of Experiment 11 was to establish the point at which OSM, crowding, and most importantly the interaction between them occurs within the object processing hierarchy, and whether attentional processes are involved in this interaction. The results of this study, unfortunately, revealed no significant effect of OSM and no significant interaction between OSM and crowding. A significant effect of crowding was revealed in the N1 amplitude. However, on closer inspection it became clear that these effects did not appear to be associated with crowding itself. Rather, these effects were perhaps more associated with the stimulus display presentation. Consequently, the results of this study were unable to provide electrophysiological information about the stage at which the interaction between OSM and crowding occurs (or at what stage either of the phenomena occurs individually). Given the fact that crowding and OSM both failed to have an effect on early visual related components indicates that perhaps later re-entrant and/or attentional processing is required in these phenomena. Equally, it could be that the paradigm used in Experiment 11 was not sensitive enough to detect the effects of these phenomena. As such, the examination of later occurring visual ERPs such as N170 and N2pc are needed to examine this interaction between OSM and crowding further.

Chapter 5
Discussion

This chapter starts by briefly reiterating the original aims of this thesis as given in Chapter 1. The findings of the three experimental chapters will then be summarised. From this point the chapter will aim to integrate the findings of these three chapters and discuss them in relation to existing theories of OSM and crowding. The findings will also be discussed in terms of the object processing hierarchy (Breitmeyer, 2014) and in relation to the recently presented foveal OSM (Filmer et al., 2015). Finally, the potential future research directions in light of the results of this thesis will be highlighted.

5.1 Aims of the thesis

The initial aim of this thesis was to revisit the question of the role of set size in OSM. The original theoretical description of OSM postulated that the phenomenon occurred only when the target was presented in an array of distractors (Di Lollo et al., 2000). If the target was the sole item in the display, Di Lollo and colleagues (2000) claimed that OSM would not occur. They suggested that this relationship between distractor set size and attention was because OSM could only occur when spatial attention was diffuse. It was argued that set size is essentially a proxy for the spread of spatial attention (Di Lollo et al, 2000; Treisman & Gelade, 1980; Wolfe, 2000). When the target is just one of many items in a display this means that the target is not initially the focus of attention and consequently is vulnerable to masking.

Recent research however has shown that OSM seems to occur independently of variations in set size (Argyropoulos et al., 2013; Filmer et al., 2014; Filmer et al., 2015). Most problematic for Di Lollo and colleagues' (2000) original theoretical account of OSM (the OSTM) is that such studies showed that substantial OSM occurred even with a set size of one (i.e. just the target in the display) when performance in this condition was within a measureable range. It was found that the addition of further display items seemingly had no effect on the OSM effect itself (though overall perceptibility for unmasked and masked conditions tended to be reduced as set size increased). These researchers (Argyropoulos et al., 2013; Filmer et al., 2014; Filmer et al., 2015) argued that the notional set size effects on masking originally reported by Di Lollo and colleagues were, in fact, mere artifacts of constrained performance with small set size displays. Where performance under such conditions was brought within a measureable range (e.g. by having a more difficult discrimination task) OSM was revealed to occur with a single target and the interaction between set size and masking disappeared.

Some subsequent research however indicated that set size might actually still play a role in OSM, at least under some–as yet to be identified–circumstances (Pilling, 2013). This study was one which did not have set size effects in OSM as its primary research interest. However a comparison across two between participant set size groups (set size=4; set size=8) found a significant difference in masking exhibited by the groups. This effect was under conditions where there were no apparent ceiling effects in the data and where performance was clearly within a measureable range in all conditions. These data seem to counter the claim that set size effects on OSM are merely an artifact of constrained performance (Argyropoulos et al., 2013; Filmer et al., 2014), at least in some cases. These findings therefore suggest that perhaps the rejection of set size effects in OSM was premature. One aspect of the Pilling (2013) study which seemed notable compared to the earlier studies of both Argyropoulos et al (2013) and Filmer et al (2014) was the use of a digit identification task (rather than a Landolt discrimination task). It was questioned if this aspect of the display was somehow a factor which would explain the difference in terms of the effect of set size on OSM. This was used as a starting point for the investigation of set size in OSM in this thesis.

To pre-empt the discussion of the findings, the experiments in Chapter 2 repeatedly and consistently revealed a set size effect in OSM under a variety of conditions including those very similar to that used in Argyropoulos et al (2013) and Filmer et al (2014), in terms of stimulus type and task requirements. Chapter 3 then aimed to explore if the effect of set size on OSM was actually a consequence of crowding of the target due to the greater proximity of distractors to the target with increased set size. Chapter 4 aimed to reveal the underlying processing stage or stages at which the interaction occurs between crowding and OSM which was found in Chapter 3. That is, whether this relationship between crowding and OSM involves a late occurring interaction as is indicative of OSM (Di Lollo et al., 2000) or an early interaction as is indicative of crowding was under investigation (Wilkinson et al., 1997).

5.2 Chapter summaries

Chapter 2

Chapter 2 of this thesis (the first experimental chapter) described five experiments which all investigated the role of set size in OSM. Recent research has raised questions over whether large set sizes are actually necessary for OSM to be produced (Argyropoulos et al., 2013; Filmer et al., 2014). As such, these experiments used a stimulus type that has been shown to produce substantial masking (i.e. digits; Pilling, 2013) as well as Landolt stimuli and numerous reporting methods (i.e. identification, discrimination, detection) in an attempt to fully explore the set size effect in OSM. An interaction between set size and mask duration was repeatedly and reliably produced regardless of the task complexity, task type or stimulus type used.

These findings suggest that at least under certain circumstances, set size is important in OSM and can substantially increase its magnitude. It is worth noting however that these studies did provide clear and unambiguous support for one of the claims of Argyropoulos et al (2013) and Filmer et al (2014). The findings showed that reliable and substantive OSM could be observed even when the target was presented in the absence of any distractors. That is, OSM was produced even when set size equalled 1. This observation is contrary to the original claim of Di Lollo et al (2000) and the predictions of the CMOS (the formal computational model of OSM proposed by Di Lollo et al, 2000). However the results departed from both Argyropoulos et al (2013) and Filmer et al (2014) in finding that set size did not only affect performance but also masking itself. In this respect the results were consistent with Di Lollo et al and with the CMOS predictions. Why, then, does the set size variable influence masking? This was the question which occupied Chapter 3.

Chapter 3

Chapter 3 explored whether the set size interaction produced in Chapter 2 could be explained by crowding of the target (i.e. increased spatial proximity of the distractors) with increased set size. The findings of Chapter 3 revealed that when set size and crowding were decoupled from one another set size had an overall effect on performance but did not interact with OSM. In contrast, crowding not only had an effect on overall performance but also interacted with OSM. That is, crowding substantially increased the magnitude of OSM while set size had no meaningful effect on OSM. Thus, it seems that the set size effect produced in Chapter 2 was in fact an artifact of crowding of the target at the larger set sizes.

When the interaction between crowding and OSM was investigated further it became evident that it was much more wide ranging than initially anticipated. In fact, a clearly non-monotonic (inverted U-shaped) character of the interaction was revealed whereby OSM was greatest at medium target-flanker distances. The data presented in this Chapter (Experiment 10) also gave some indication that this inverted U-shaped function of the interaction between crowding and OSM scaled somewhat with increased display eccentricity. This suggests that the distance at which distractors affected the target was greater with increased eccentricity, as is expected of crowding (Bouma, 1970). However, there was no strong evidence to suggest that the magnitude of the effect increased with increased eccentricity.

The results of this chapter therefore presented a more complicated interaction between crowding and OSM than was originally predicted. The inverted U-shaped function of the interaction between OSM and crowding perhaps indicates an effect of OSM on crowding rather than an effect of crowding on OSM as was initially expected. Specifically, these findings indicate that OSM led to an increase in the crowding window i.e. the distance at which flankers effectively crowded the target was greater when there was a trailing mask.

These findings therefore show parallels with those of "supercrowding" (Vickery et al, 2009) in which the window of crowding is extended by weak, low level masks (e.g. outline and pattern masks). What is interesting about this is that OSM has been classified as occurring *later* within the object processing hierarchy than crowding (Breitmeyer, 2014; Breitmeyer; 2015). Were this the case then while crowding might be able to influence masking, the converse should not occur. These findings therefore do not fit within such a strict processing hierarchy, at least in the form specified. Specifically, within such a linear (uni-directional) model as has been proposed there is no explanation for how a late occurring processing impairment (i.e. OSM) could enhance the impairment of one that occurs prior to it (i.e. crowding). Given this seeming disparity, an electrophysiological investigation of the time course in which the interaction occurs was performed.

Chapter 4

Chapter 4 presented an electrophysiological investigation of crowding and OSM as they occurred in the conditions of Chapter 3. This experiment aimed to examine the stage(s) in the visual processing hierarchy at which crowding and OSM occur individually and the stage at which the interaction between crowding and OSM occurs.

This experiment replicated the inverted U-shaped interaction between crowding and OSM in the behavioural data (though here only three-target flanker distances were given). That is, the effect of OSM was strongest at the medium target-flanker distance. In terms of the EEG data, the only significant effects that were found were related to crowding in the N1 component. However, when evaluating this effect it became clear that it did not seemingly relate to crowding itself. Specifically, this effect related to increased negativity associated with N1 at the medium target-flanker distance regardless of masking. In contrast, the amplitude at the small and large target-flanker distances were almost equivalent. As such, the findings of this experiment unfortunately revealed little about the underlying nature of the OSM×crowding interaction and the stage at which it occurs. These EEG findings may indicate that the interaction effect is not associated with any reliable electrophysiological correlate. Alternatively it may be that the visual ERPs isolated and analysed in this experiment were ones reflecting perceptual processes too early to exhibit an effect of OSM on crowding. Finally it may be that the paradigm itself and its implementation in EEG were unable to reveal the electrophysiological correlates of the effect.

5.3 Theoretical accounts of OSM and crowding in relation to the thesis

5.3.1 The thesis findings in relation to the OSTM

The OSTM was discussed in section 1.4.2 of the first chapter. To recap, the OSTM postulates that OSM occurs as a consequence of re-entrant processing. It is claimed that OSM occurs when the mask offsets after the target because it causes a mismatch in the information received at the low level (mask alone) compared to that contained in the high level processing areas (target and mask).

According to the model, this mismatch is most likely to occur when the time taken for attention to reach the target is delayed i.e. there is a delayed time to contact. The role of spatial attention is operationalised within this model with the set size variable. That is, when there are multiple items presented in the display, the time taken for spatial attention to reach the target is argued to increase (Treisman & Gelade, 1980). When the display set size is large, the model proposes that it takes longer for the spotlight of attention to reach the target. Consequently, with a brief stimulus presentation, there is less time for attention to focus upon the target location. This has the outcome of making the target vulnerable to substitution by the mask percept in an iterative process of perceptual hypothesis generation, before a successful match can be obtained (Di Lollo et al., 2000). Thus, according to the OSTM, this increased time to contact, expressed as the set size variable is critical for OSM to occur.

The current research found that there is a role of distractors in OSM. However, the role of distractors found here is not in line with that proposed by the OSTM (Di Lollo et al., 2000). The findings of this thesis showed categorically that set size, and therefore the increased time to contact as described by the OSTM, is unessential for OSM to be produced. Rather, distractors were found to play a role in a way that was dismissed by Di Lollo and colleagues (2000) in their theoretical interpretation of OSM. That is, it is crowding of the target that interacts with OSM and under certain circumstances leads to increased masking.

Another key element of the OSTM is the assumed role of re-entrant processing. The findings presented here do not challenge the re-entrant model directly. They do however raise questions over the specific implementation of this model relating to the role of attention and the previously mentioned time to contact associated with this role of attention. That is, the current findings do not fit well with the current claims of increased time to contact leading to OSM. Under this current explanation the magnitude of OSM should arguably be equivalent across the different target-flanker distances in Experiments 8-11 as the set size is fixed at four items. That is, an equal number of display items should be entered into the visual search meaning the time to contact in all instances would be equivalent regardless of the distance of the flankers from the target. This is not the case however. Rather than it being purely the number of display items that are presented with the target that affected OSM, as is predicted, it is actually the proximity of those items to the target that can lead to increased OSM magnitude.

It is debatable that perhaps the proposal of increased *time to contact* is misconceived within a theory of OSM in any instance. The task undertaken with OSM is not a conventional search task, at least when looking at the standard OSM paradigm. In it the target essentially "pops out" in the display due to being the only item surrounded by the 4DM. The conditions of OSM are more akin to the situation of a disjunctive (Treisman & Gelade, 1980), or efficient (Wolfe, 1994) search task, i.e. one in which the speed with which the target is found is independent of the number of items in the display (e.g. searching for a square amongst triangles; or a red item amongst green items). As such, it is unclear why *time to contact*, and by extension set size would be deemed as important in OSM, at least in the way conceived by the OSTM. Perhaps if the mask was not such a salient spatial cue to the target, making the task more akin to a standard visual search paradigm the time to contact factor may be revealed to be of some importance; however in the conventional OSM paradigm this is logically not the case.

5.3.2 The thesis findings in relation to the OUT

The OUT (Lleras & Moore, 2003; Moore & Lleras, 2005) can be thought of as a cognitive model of OSM rather than a neurocognitive model, as the OSTM is (Di Lollo et al., 2000). This model was discussed in section 1.4.3 of the first chapter. This model focuses on the relationship between the target and the mask in terms of object token representations, rather than in terms of their neural implementation. The primary perspective of the OUT is that OSM occurs due to the target and mask being represented by a single object token. Consequently, masking occurs when the trailing mask is viewed as an update of the one existing representation (i.e. target+mask). When the circumstances favour the target being individuated from the mask in some way (in terms of the spatiotemporal and featural characteristics of the mask in relation to the target), masking is substantially reduced.

Given this focus of the OUT, it makes no explicit claims about the role of set size in OSM. Consequently, the findings of this thesis do not raise fundamental issues for the model in the same way as for the OSTM. However, the OUT also makes no explicit claims about the role of crowding in OSM and it is unclear how obviously crowding as a variable could be understood as a factor in the individuation process.

When examining the current data, it appears that the object interpretation process in OSM seems to be affected not only by the target and mask percepts but also by the other stimuli that are presented within the display. That is, OSM seems to be affected by information across the whole visual field. This would suggest that the individuation process is not local in its method and involves not only the relations of the target and mask but also somehow the distractors that are presented with the target. Therefore the OUT, in its current form, perhaps provides an incomplete explanation for OSM.

5.3.3 The thesis findings in relation to the attentional gating model

The attentional gating model of OSM (Põder, 2013) was described in section 1.5.2 of the first chapter of this thesis. This model is arguably the simplest model of OSM in terms of its description of how masking occurs in OSM. It is also, perhaps, the most parsimonious model in terms of the assumptions it makes about the architecture of the visual system. The model makes no assumptions about re-entrant processes. Instead the model assumes visual processing is explicitly feedforward in nature and that the interactions in OSM are themselves feedforward. In the model the mask is seen as a source of noise. The model postulates OSM to occur because of reduced signal to noise for the target compared to the mask when the mask offsets after the target. In the model the synchronous onset of the target and mask results in a temporal integration of the neural signals associated with the two. When the mask continues to be displayed after the target offsets, the signal corresponding to the mask is available for longer. Consequently, the increased visual noise generated by the mask becomes added to the target signal resulting in a partial or complete loss of awareness of the target and a corresponding reduction in accuracy of report of the target.

The data from the thesis can be potentially accounted for from within the framework of Põder's (2013) model. In this account the synchronous onset of the two flankers surrounding the target could be assumed to be an additional source of noise to that of the mask and therefore one which becomes subsumed with the target signal in the temporal integration process. Thus, it is possible that these flankers reduce the signal to noise ratio (SNR) in the same manner as that described for the mask. This reduced initial SNR of the target would in turn lead to more effective masking by the 4DM when it trails the target offset.

However, the current instantiation of this model does not seem to easily explain – and certainly does not predict – the inverted U-shaped function that was repeatedly observed with respect to target-flanker distance. If the distractor effect was related to increased SNR for the target, then it should be expected that this would be most prominent when the target was closely flanked by distractors and diminish thereon with increased spatial separation. Any successful model involving an attentional gating process would therefore need to incorporate the fact that the effect of OSM in relation to flankers is non-monotonic in nature.

It is currently unclear whether Põder's (2013) attentional gating model could successfully achieve this without violating the simplicity and parsimony of the model which is a large part of its appeal. One possible resolution is to assume that the initial attentional gating includes the mask but not the flankers. This would mean assuming that the crowding effect of the flankers occurs subsequent to the mask-target attentional gating process in the manner theorised for the supercrowding phenomenon (Vickery et al., 2009).

5.3.4 The thesis findings in relation to pooling theories

Pooling theories are arguably one of the most widely accepted explanations of the crowding phenomenon (Pelli et al., 2004; Põder, 2006; Wilkinson et al., 1997). These theories were discussed in section 3.1.3. However, to briefly summarise, pooling theories claim that crowding occurs due to the spatial integration of the target and surrounding flankers. This pooling is increasingly likely with increased eccentricity due to the much coarser spatial resolution of the visual system in the periphery of the visual field (Desimone & Schein, 1987). These pooling theories essentially attribute crowding to interactions in fairly low level processing. Within these theories, crowding is the consequence of the target and flanker features becoming integrated. This leads to a muddled percept of the target causing the target to be difficult to identify (Pelli et al, 2004).

There is potential that the effect of OSM on crowding leads to a degraded representation of the target in early vision. This greater degradation may mean that the flankers become integrated with the target percept even when they are more widely spread apart than is the case with the traditionally supra-threshold stimuli which are used in most crowding studies. Factors such as reduced stimulus presentation time (Kooi et al., 1994) and increased flanker contrast (Rashal & Yeshurun, 2014) have been found to cause greater crowding. Interestingly, recent research has shown that the combination of these factors within a crowding paradigm (i.e. reduced duration time and increased flanker contrast) can have a super-additive effect, substantially increasing the crowding window paralleling the "supercrowding" effect (Soo, Chakravarthi & Andersen, 2015).

This type of "supercrowding" explanation is supported by the evidence in Chapter 3 that the effect of OSM on crowding tended to scale with eccentricity. Thus, this indicates that the masking of the target was adding to the likelihood of distractors being integrated with the target given the coarser spatial resolution in the periphery.

However, as discussed in section 5.2, the electrophysiological data presented in Chapter 4 revealed no early visual processing effects of OSM on crowding, at least none that could be determined in the electrophysiological responses to the target stimulus. This might suggest the potential to reject a purely low level integration account of the effect of OSM on crowding in terms of pooling mechanisms. However, it must be noted that the EEG data presented in this thesis do not conclusively rule out the existence of low level activity related to either crowding or OSM. The question of the EEG responses will be looked at in a section 5.7 of this chapter.

5.4 The role of set size in OSM

The findings of this thesis (specifically Experiment 7) showed that set size had an overall effect on target perceptibility but did not influence OSM. That is, when the target was presented with increased numbers of distractors, overall target identification accuracy was reduced. These findings are in line with those of Argyropoulos et al (2013) and Filmer et al (2014) who both reported that the consequence of set size was only to reduce the overall perceptibility of the target.

It seems unlikely that this set size effect relates to "time to contact" given the fact that the OSM paradigm used was not a traditional search task (i.e. the target was likely distinct in the display given the surrounding 4DM; as discussed in section 5.3.1). Perhaps the role of the increased number of distractors with the set size manipulation is to increase the noise in the visual system. This has been reported in the visual search literature previously (Baldassi & Burr, 2004; Eckstein, Thomas, Palmer & Shimozaki, 2000; Palmer, Ames & Lindsey, 1993).

Though manipulations of set size were initially found to influence OSM, these effects were found to be an artifact of crowding, a factor which tends to co-vary with set size. That is, as set size increased, the distance between the target and the nearest surrounding distractors decreased. Thus, the results presented here show that at the very least, set size is not an essential requirement for OSM. Rather, it is the distance at which the target is surrounded by the distractors that is important to increase OSM magnitude.

These results are therefore contrary to those reported by Di Lollo et al (2000). That is, strong masking was produced across this series without the need for increased set size. These findings show therefore that at the very least, set size is not essential to produce OSM despite the claims of the OSTM. Rather, the results presented here support the claims of Argyropoulos et al. (2013) and Filmer et al. (2014), at least in this respect. Both of these investigations reported that strong masking could be produced in the absence of a set size effect, as was replicated in Chapter 3 (particularly Chapter 7). However, those studies argued that the interaction between set size and masking was an artifact of constrained performance (i.e. that performance in the small set size conditions was outside a measurable range); the current studies found the interaction to be the consequence of crowding of the target with large set size displays.

To date there have been a number of investigations of OSM that have focused on the role of set size (Di Lollo et al., 2000; Goodhew et al., 2012; Jannati et al., 2010). In light of the current findings, these findings could be argued to be potential proxy examinations of crowding in OSM. That is, it is typical with examinations of set size in OSM for set size and crowding to co-vary, as was the case in Chapter 2. Thus, as was shown in Experiment 7 of Chapter 3, it could be that in these instances crowding of the target, not set size, caused increased masking.

5.5 The relationship between crowding and OSM

The phenomena of crowding and OSM have previously been considered to be largely distinct both in terms of the type of processing impairment they cause and also in the stage at which they occur (Breitmeyer, 2014; Breitmeyer, 2015; Chakravarthi & Cavanagh, 2009). The findings of this thesis however show that these phenomena clearly interact. Initially it was viewed that this interaction was an effect of crowding on OSM whereby the magnitude of OSM was increased under conditions of target crowding. However, with further investigation it became evident that this interaction represented an effect of OSM on crowding whereby the range of crowding was increased under conditions of OSM.

The best interpretation of this inverted U-shaped function of the crowding×OSM interaction is that OSM has a causal effect on the effective range of crowding when the target is masked. To specify, under conditions of classical crowding (i.e. in unmasked [0ms mask] conditions), reporting accuracy was poor when the flankers were presented near the target and monotonically increased with increased target-flanker distance. If the interaction between crowding and OSM represented an effect of crowding on masking, it would be expected that the modulation of masking (i.e. the performance difference between 0ms and trailing mask conditions) would bear a direct relationship to the pattern of crowding. That is, the expectation would be that substantial OSM would be produced at the smallest target-flanker distance and would diminish with increased target-flanker distance. This means that once flankers fell outside the crowding window (as defined by Bouma's law, 1970) no effect of crowding should have been produced, as was the case in the uncrowded condition.

This pattern of results was not found under conditions of OSM in this thesis where target-flanker distance was varied however. Rather, these results seemed to show that fairly weak OSM was exhibited at small target-flanker distances, becoming progressively stronger as flankers shifted outwards to a peak at medium target-flanker distances, beyond which masking substantially declined again. It is therefore difficult, if not impossible to interpret this effect in terms of an effect of crowding on masking given that the pattern of masking does not display the characteristic crowding function.

In contrast, when these findings are evaluated in terms of an effect of masking on crowding, like that of "supercrowding", the result appears much clearer. In these instances, the expectation would be that the range of crowding is extended under conditions of masking. This would be exhibited as a less steep decline in crowding than found without masking (i.e. the range of crowding would be extended). In terms of masking, it would be expected that the masking function (the difference between the unmasked and masked conditions) would exhibit an inverted U-shaped function.

This is precisely what was found by Vickery et al (2009) and what was found in the current series of experiments. Thus, the explanation of an effect of masking on crowding provides a much better fit to the data and a more coherent explanation for the findings of this thesis than an effect of crowding on masking. Moreover, it fits empirically with the findings of Vickery et al's (2009) "supercrowding" experiments, giving evidence that this effect can be produced with a different type of masking paradigm. Specifically these findings show that “supercrowding” can be produced using a high level form of masking, that being OSM (Breitmeyer, 2014).

It is however worth discussing alternative explanations which might be levelled at this effect. It could be argued for example that this effect owes something to how attention becomes distributed across the stimulus display. In such an explanation, it could be argued that somehow the spatial position of the distractors determines how much masking the target receives through varying the extent to which the target is attended.

Presumably the point at which masking is greatest would be related to the point where attention is least focused on the target (i.e. more wide dispersion of stimuli across the whole stimulus display). The design of the displays which examined crowding in terms of target-flanker distance (i.e. Experiments 8-11) always ensured that the target was positioned opposite a distractor in an attempt to equalise this attentional distribution across the display. This in itself does not rule out the possibility of a role for attention in explaining the pattern of results obtained in the masking experiments of Chapter 3. There are however other factors that pose challenges to any explanation described in terms of attentional mechanisms.

Firstly, recent evidence has suggested that focused spatial attention has at best a modest effect on OSM and in many cases has no effect at all (e.g. Filmer et al., 2015; Pilling et al., 2014). For instance, Pilling et al (2014) found no effect of attention in four of five experiments in which spatial attention was manipulated exogenously, prior to target onset, to be either diffuse or focused at the target location. In the one experiment where an attentional effect was significant it accounted for a difference of only around 5% in terms of the change in masking observed. This is contrasted with the substantial effect of flankers on the OSM experiments in this thesis. Thus, the large magnitude of the effect on OSM seems unlikely to be a consequence of attentional effects.

Fundamentally it is unclear why an attentional explanation would predict an inverted U-shaped masking function of the kind demonstrated in the experiments presented here. It might be assumed for instance that attention tends to initially be deployed towards the biggest cluster of items. This would explain why masking was weak at the small target-flanker distances as when the target is presented within a cluster of items attention could be drawn towards it. This means that the target is therefore given priority for processing in this configuration. However, this should also mean that masking would be strong when the flankers cluster around a distractor opposite the target as attention should be deployed to this (non-target) location first. This would indicate that the "time to contact" towards the target would be delayed resulting in substantial masking.

This was not observed in the results presented here however. In the majority of experiments, the masking effect was stronger when the flankers closely surrounded the target than when it closely flanked the distractor. Furthermore, this attentional account cannot easily resolve the fact that overall perceptibility of the target was most impaired when the target was closely flanked. That is, the grouping of the stimuli did not seem to have a facilitatory effect on target processing. Thus, this pattern of the data does not seem to fit easily with an attentional explanation, at least not one described in terms of "time to contact" as discussed here. Given these factors, it seems that the explanation of an effect of OSM on crowding is the more parsimonious one and fits best with previous findings.

What is still unclear however is whether the interaction between crowding and OSM is in some way attentional in nature. To specify, crowding has traditionally been considered as a low level processing impairment. Consistent with this claim is the fact that crowding effects are largely insensitive to the distribution of attention (Levi, 2008). In fact, crowding effects reliably occur even when the target locus is under focused covert attention (Levi, 2008). For example, crowding can still be produced when the participant is aware of the exact location and at what time point the target will appear (Levi, 2008). It has therefore been argued that a lack of attentional deployment cannot explain crowding phenomena. This would suggest that the effect of OSM on crowding in turn would not require diffuse spatial attention.

This picture is not entirely clear however: other evidence suggests that crowding can be modulated by attention. For example, crowding has been found to reduce substantially when the target location is cued (Freeman & Pelli, 2007; Strasburger, 2005; Yeshurun, & Rashal, 2010), and when attention is devoted towards the target location (e.g. the crowding window is far greater when participants are required to conduct an attentionally demanding secondary task; Dakin, Bex, Cass, & Watt, 2009), as has been found with OSM. Thus, it has been argued that perhaps crowding produces a reduction in attentional resolution (Intriligator & Cavanagh, 2001). Under these conditions therefore it could be posed than the inclusion of OSM leads to increased degradation of the attentional resolution. This would then result in the increased distance over which crowding affects target perceptibility.

Unfortunately, the EEG evidence in this thesis (Experiment 11) which attempted to understand the time course of these effects was inconclusive. However, this study failed to find any significant effects of either crowding or OSM on *P1* or *N1* amplitude or at any other point within the 250ms time window observed. It is worth noting that these ERP components are relatively low level, sensory visual components. It could be argued therefore that the lack of any significant effect on these components suggests that these phenomena are perhaps higher level in nature. However, it could also be that this experiment was not sensitive enough to effects in these early visual components.

5.6 OSM in relation to local and non-local processing

One of the core attributes of OSM, which sets it apart from classical forms of masking such as pattern and metacontrast, is that it is largely "non-local" in nature. In both pattern and metacontrast masking the occurrence of masking is dependent on the target and mask occupying the same or closely nearby locations. This seems to be far less relevant a factor in OSM. For instance, OSM can produce substantial masking whether the four dots are located at a distance of 1.20° visual angle or only 0.17° degrees from the target (e.g. Di Lollo et al., 2000; Guest et al., 2011). It is not necessary for the four dots to surround the target to produce an effect. The four dots can even produce OSM when the mask is some distance away from the target on screen as long as the two are connected by apparent motion (see Lleras & Moore, 2003; Pilling & Gellatly, 2010).

The fact that OSM occurs even where target and mask are spatially disparate has been taken as reasonable evidence to suggest the involvement of high level visual areas. It is well established that as the visual system is ascended, the spatial receptive fields of cells become increasingly broad (Desimone & Schein, 1987). The finding (presented here) that – under conditions of OSM – crowding also displays this broad spatial sensitivity to flanker positions across wide regions of the visual field may not be coincidental. Indeed the spatial extent of "supercrowding" under conditions of OSM is quite profound. The fact that crowding exhibits this sort of broad spatial profile across large portions of the visual field indicates that crowding (or "supercrowding"- if it is a distinct process) must involve processes occurring at a fairly high level in the visual system.

It is plausible that this finding in terms of the large spatial scale in which the crowding×OSM interaction operates fits well with the proposed role of re-entrant processing in OSM (Di Lollo et al., 2000). Furthermore, some recent evidence in the crowding literature has suggested a requirement of re-entrant processing for crowding to occur (Clark, Herzog

& Francis, 2014; Jehee, Roelfsema, Deco, Murre, & Lamme, 2007). The nature of this re-entrant process means that the visual system is expected to receive, and be responsive to, input across the broad visual field (Allman et al., 1985; Zeki, 1993).

5.7 OSM, crowding and the object processing hierarchy

The discovery of the crowding×OSM interaction raises questions over the current proposed structure of the object processing hierarchy (Breitmeyer, 2014; Breitmeyer, 2015; Breitmeyer, Koç, Öĝman & Ziegler, 2008). It should be noted that the nature of the object processing hierarchy is not something that this thesis explicitly set out to test. However the findings (of Chapter 3 in particular) seem to provide clear implications regarding this proposed hierarchy. The current instantiation of this hierarchy includes a number of levels of unconscious processing; the cortical processing that occurs increases with increased hierarchical levels.

Within this hierarchy binocular rivalry and CFS are argued as the earliest occurring visual blinding phenomena. Backward masking by noise (pattern) and metacontrast masking are viewed as occurring at a functional level later than these phenomena but earlier than the AB and crowding. OSM is presented as the latest occurring phenomenon. This positioning of crowding, and of OSM as functionally distinct is based predominantly on the findings and interpretation of Chakravarthi & Cavanagh (discussed in section 3.1.6) and the proposed requirement of attention for OSM to prevent awareness as claimed by the OSTM (Di Lollo et al., 2000; see Figure 12 for a diagrammatic display of this hierarchy; Breitmeyer, 2014).

The current research provides no evidence to raise questions over how crowding relates to other phenomena that are argued to occur earlier than it in the object processing hierarchy. What the results seem to challenge is the claim that OSM is a later stage process than crowding (Breitmeyer, 2014; Breitmeyer, 2015). In particular the fact that OSM leads to substantial modulations of crowding (by increasing the crowding window) and shows parallels with "supercrowding" effects is difficult to reconcile within this hierarchy.

For OSM to impact crowding in this way it would require OSM to occur earlier in the object processing hierarchy than crowding, at least within a strict linear model of processing as Breitmeyer (2014) seems to present. It is hard to see how OSM could increase the crowding window (i.e. the distance at which the distractors affected the target) if crowding of the target occurs prior to OSM. One solution is to argue that OSM is misplaced in the hierarchy and should be placed below crowding. There are difficulties with such a reformulation however. For example there is evidence for the functional distinctiveness of crowding and OSM with OSM occurring later. Specifically, OSM impairs categorical processing (Chen & Treisman, 2009) whereas crowding does not (Breitmeyer, 2015; Levi, 2008). Moreover, this explanation would be inconsistent with the findings of Chakravarthi and Cavanagh (2009) in relation to the masking of flankers in crowding.

It is worth noting however that there are potential alternative explanations for the findings presented by Chakravarthi and Cavanagh (2009). For instance, these findings could potentially be explained by the fact that OSM was unable to protect against crowding as both phenomena were undergoing processing at the same time. Crowding has been shown to produce substantially larger effects than OSM in regards to hindering target perceptibility (Pelli et al., 2004). This stronger crowding effect was replicated in the current series of experiments. As such, any potential beneficial effects of OSM would be overpowered by the stronger crowding effects.

Another explanation for the Chakravarthi and Cavanagh (2009) results relates to the spatial factors of OSM. Strong OSM has been found even at locations adjacent to the target due to the poor spatial resolution in the visual periphery (Lleras & Moore, 2003; Moore & Lleras, 2005). This means that contrary to OSM producing a lack of crowding suppression, it could potentially have had an additive or "supercrowding" effect even though the mask surrounded the flankers. This potential for "supercrowding" is conceivably even stronger given the design of their stimulus display. To specify, in the Chakravarthi and Cavanagh experiments the four flankers surrounded the target. This means that two dots from each of the four masks were actually surrounding the target location as well as the mask. Inspection of the relevant figures (particularly Figure 2) from Chakravarthi and Cavanagh does in fact support this claim. It can be seen that there was a small albeit non-significant drop in performance when OSM was used in contrast to the marked increase in performance with the other mask types.

Nevertheless, it is possibly incorrect to even attempt to produce a classification of phenomena in terms of this strict, regimented processing hierarchy. Indeed from the perspective of a re-entrant processing framework (e.g. Di Lollo et al., 2000; see section 1.4.1 of Chapter 1) it might be argued that the imposition of such frameworks is possibly misconceived if visual processing is cyclical rather than feedforward in nature within the architecture of the brain. Hierarchies are still assumed to exist within re-entrant frameworks. Indeed Di Lollo et al's (2000) model specifically refers to interchanges between higher and lower level regions. However in the re-entrant architecture the interactions can potentially occur through ascending as well as descending pathways. An alternative explanation to them occurring within a strict object processing hierarchy therefore may be that they access separate, equally complex networks of cortical processing with some of this cortical processing being shared by the two networks, (Breitmeyer, 2014). It is plausible that within such a system of networks re-entrant processing would likely be a key element of visual processing.

5.8 Neural underpinnings of crowding and OSM

The EEG experiment (Chapter 4) revealed little about the neural basis of crowding and OSM. Firstly, no clear *P1* component was evident in the electrophysiological responses. It is not entirely clear why this component was not apparent in the data. It must in some way reflect some aspect of the temporal dynamics of the display, for instance the onset of the fixation cross in relation to the target. Alternatively absence of the P1 could be a consequence of the high attentional demands of the task. It has been argued that the P1 reflects the "cost of attention" (Luck, 1994). The P1 is known to be diminished when a target is presented outside the region in which the participant was attending (Mangun & Hillyard, 1991). It is possible that participants' attention tended to be for some reason particularly focused at the central fixation cross within the task. A consequence of this might be that attention tended to be reduced towards the target stimulus at the point of its onset leading to an absence of a detectable P1. While there was no P1 evident an earlier positive deflection was found across all conditions (labelled a 'P50'). This visual P50 is not something conventionally found in visual ERPs. It is difficult to argue that this is a P1 component because it is around 50ms too early in its peak. Again it is difficult to understand the reason for this aspect of the data. This visual P50 presumably reflects some aspect of early processing of the target array. Nevertheless, there was no evidence that this component was modulated by any of the conditions in the experiment.

Importantly, as was discussed in Chapter 4, the EEG analysis failed to reveal any obvious neural correlate of the reliable and substantial interaction between crowding and OSM found in the behavioural data. There was no detectable modulation of the amplitude of early visual ERPs associated with either OSM, crowding, or the interaction. In failing to find any main effects of OSM and crowding the data failed to replicate some previous findings in the literature (e.g. Wynn et al., 2013; Chicherov et al., 2014). However, there are a number of differences between these studies and the current investigation (see section 4.3 for further discussion of this). These results should be seen in the context of the rather limited extant literature on the EEG correlates of both crowding and OSM. This is perhaps an indication of the difficulties in isolating reliable neural correlates of these phenomena of awareness.

The only significant effect that was produced in Experiment 11 was an effect of target-flanker distance on *N1* amplitude. This effect was manifested as increased negativity at the medium target-flanker distance. However this effect did not bear any simple relationship with the behavioural data. The increased negativity was just as evident for the unmasked as the masked trials. This makes it difficult to argue that the effect had anything to do with crowding, masking or the interaction between the two. An explanation for this observed *N1* modulation can be cast in terms of attentional processes. The *N1* is known to be sensitive to selective attention (Clark & Hillyard, 1996; Luck, 2014). For example, the *N1* tends to be larger for stimuli that are attended compared to those that are not attended (Clark & Hillyard, 1996).

It may be therefore that under conditions of the medium target-flanker distance, there is somehow a greater attentional deployment or increased discrimination process (e.g. Vogel & Luck, 2000) for this display configuration compared to the other configurations at the near and far target-flanker distances. Therefore, it could be that under conditions of the medium target-flanker distance, attentional deployment is able to be drawn to the target location faster, or attention is more able to focus on the target locus under these conditions. Thus this may result in a greater deployment of attention to the target compared to with the other target-flanker distances. It must be noted that the effect may be related to the spread of attention more generally, rather than specifically to the focus of attention on the target. It may be that at the medium target-flanker distance where the individual stimuli are most spaced apart attention itself is at its most diffuse, an effect which is reflected in the amplified N1.

It should be noted that this “attentional” effect should be interpreted with caution. The modulation of the N1 was found across only a small subset of electrodes. The effect was not predicted and may be no more than a statistical anomaly. Given this it is best not to “over interpret” or speculate too much about the underlying processing associated with this finding. This effect may indeed say something about differences in attention across the display types. However, the fact that this effect was found across both the unmasked and masked conditions means that it is difficult to relate it in any meaningful way to the interaction between crowding and OSM that was found in the behavioural data.

Moreover, given the fact that *time to contact* does not seem to be a major factor in the observance of OSM (e.g. Pilling et al., 2014), it seems increasingly likely that this putative attentional effect in the N1 is superfluous to the masking effect. Thus, to conclude it does not seem that this *N1* modulation is a neural correlate of the effect of OSM on crowding. As such, this electrophysiological investigation of the effect of OSM on crowding was unsuccessful in discovering any more about the underlying processing stage(s) at which the crowding×masking interaction occurs.

5.9 The effect of eccentricity on OSM

Initially OSM was considered to be a phenomenon which was most evident in the visual periphery. The majority of studies of OSM have tended to present the target stimulus in the periphery (e.g. Enns, 2004; Gellatly et al., 2010; Guest et al., 2011; Jiang & Chun, 2001; Lleras & Moore, 2003; Pilling et al., 2014; Reiss & Hoffman, 2007). Recent research (Filmer et al., 2015) has found that OSM can be produced in the fovea, when the target is alone in the display and when it is overtly attended. This research used a single target (i.e. no distractor items were presented) in the fovea in a task in which there was no spatial uncertainty as to the target location (the target was always presented at fixation). The fact that the target was presented in isolation and at fixation ensured that full attentional resources were available for target processing. Filmer et al found that strong OSM was produced in the fovea, and crucially with full attentional resources available to identify the target. This seems to suggest that there is nothing inherently special about the visual periphery in terms of OSM, despite the fact that most OSM experiments seem to have been designed with the assumption that the phenomenon is predominantly of the visual periphery.

What is currently unclear is how the effects of crowding, as found in this thesis, relate to the evidence of foveal OSM. That is, it is not clear whether flankers would have any effect under the conditions used by Filmer and colleagues. It is expected that flankers would at most produce a very small crowding effect as crowding itself has been shown to have little to no impact on target perceptibility when the target is presented in the fovea (Gurnsey et al., 2011; Levi, 2008; Whitney & Levi, 2011).

However, it is worth noting that the paradigm used by Filmer and colleagues (2015) is not an entirely typical OSM paradigm. Filmer and colleagues used a forward mask prior to target presentation. This forward mask was used ostensibly to reduce overall target perceptibility, keeping accuracy within a measurable range, particularly in the unmasked condition. However, it is entirely possible that the use of this forward mask was somehow crucial to the OSM effect produced. That is, this forward mask may have been crucial to degrading the target percept and therefore increasing its vulnerability to being masked by the four dots.

It is arguable therefore that this examination of foveal OSM requires further investigation. Specifically, it is important to decouple the effect of the forward mask from that of OSM in order to be able to fully understand the relationship between this type of foveal OSM and the type of OSM that was produced in this thesis. There are certainly other ways of keeping performance within a measurable range without having to resort to forward masking, for instance having an adjustment task in which the observer must adjust a test stimulus to match the target orientation (e.g. Pilling, Guest & Edwards, 2015). Such an adjustment paradigm, in contrast to the more standard forced-choice decision or identification paradigms, produces a reliable amount of errors even under unmasked conditions; it thus eliminates concerns about ceiling effects.

Thus, it remains to be seen exactly how OSM varies as a consequence of foveal versus peripheral presentation. It also remains to be seen to what extent eccentricity is a factor when the extent to which a peripheral target is varied in terms of its angular distance from the point of fixation. Certainly it would be useful to look at the role of eccentricity in OSM in a systematic manner. The thesis did begin to investigate this issue of eccentricity but from the perspective of eccentricity being a major variable in the crowding phenomenon. Given that, this examination of the way in which OSM scales with eccentricity was only conducted over a restricted range in this thesis. This was done because these eccentricities are ones where it was expected that crowding would be amplified (i.e. by moving the target further into the periphery than has been done in OSM experiments previously).

Here it could be seen that increasing the eccentricity of the target did tend to lead to stronger OSM and that the interaction between OSM and crowding tended to show a peak, in terms of masking, at increasingly larger target-flanker distances. Such effects attest to the possible commonality of some of the mechanisms underlying OSM and crowding. However the question of foveal and non-foveal presentation and of the effect of distractors under these conditions still awaits further extensive study. It may be, for instance, that when masked by OSM even foveal targets can exhibit significant and reliable crowding due to the weakening of the target percept that OSM produces. Such work might be helpful in revealing the neural underpinnings of the two phenomena in terms of the hierarchical stage at which the two coincide.

5.10 Broader implications of the thesis findings

The main aim of this thesis was to understand the nature of distractor effects in OSM in order to further understand the mechanisms in this form of masking. This thesis has produced findings that provide implications for our understanding of visual processing. In particular, as earlier discussed, the findings seem to challenge the established view of where OSM resides within the object processing hierarchy (Breitmeyer, 2014; Breitmeyer, 2015), or at least suggest that this view is an incomplete one. However, it is worth also speculating about the possible implications of the findings of this thesis within a broader context in terms of more "real world" situations.

The finding, in particular, that OSM increases the crowding window, has implications for our understanding of visual awareness and research developments relating to it. Such findings are important to bear in mind in human factors research when designing dynamic visual displays. This is particularly the case for the design of displays where the information is highly critical, such as of the kind found in the "glass cockpit" displays of a modern airliner or the heads-up displays (HUDs) used in jet fighters. In such situations pilots are presented with a constant stream of rapidly changing visual information, some of it presented only briefly (Previc & Ercoline, 2004). In this situation it is critical that all relevant information is efficiently detected. Failures of visual awareness in these situations could potentially be fatal and are problems which need to be minimised in the design of such systems (Varakin, Levin & Fidler, 2004)

Clearly such information should be presented according to the best understood principles of vision. The effects of masking and crowding (or visual "cluttering") are generally known about by human factors researchers; their effects are often taken into account or avoided in the design of information displays (e.g. Doyon-Poulin, Ouellette, & Robert, 2014; Kim et al., 2011; McCann, Foyle, & Johnston, 1993; Moacdieh & Sarter 2015). Where the presented information is constantly changing over time and where new information is overlapping or surrounding the position of previously presented information, masking will tend to occur. The studies presented here show that, because masking and crowding strongly interact, such tendencies will be exacerbated where there is a lot of visual 'clutter'. Situations which produce very little masking by themselves, or ones where the effects of visual clutter appear to be minimal may actually have a strongly detrimental effect when the two factors are presented in combination. The findings of this thesis indicate that the temporal and spatial relationships between presented objects need to be assessed at the same time, otherwise it is likely that the likelihood of visual information being detected or identified may be overestimated. If anything the findings of this thesis, along with a growing body of other findings (Ghose, Hermens & Herzog, 2012; Hermens, Luksys, Gerstner, Herzog & Ernst,. 2008; Herzog, 2007; Lev & Polat, 2015; Yeshurun, Rashal & Tkacz-Domb, 2015) show that the spatial and the temporal factors of vision are closely interrelated and that this needs to be taken into account in the design of any display system.

Another potential area that these research findings could be relevant for is dyslexia. Crowding is already recognised as a factor that an influence dyslexia (Martelli et al., 2009). Furthermore, using a metacontrast paradigm several studies have found that dyslexics exhibit abnormal patterns of masking (Edwards, Hogben, Clark, & Pratt 1996; Skottun, 2001; William, Molinet, & LeCluyse, 1989, Williams & LeCluyse, 1990). Exactly how such differences would manifest themselves when crowding is introduced to such a masking paradigm is a subject for further research. As yet no study has even looked specifically at OSM masking in dyslexics. However the results of this thesis suggest that comparing the individual and combined effects of crowding and masking may be useful in further revealing the differences in visual processing which occur in the dyslexic condition. One possibility might be for instance that the distance at which other letters or words interfere with word recognition could be much greater under situations where there is rapidly changing information.

5.11 Future directions

The findings of this thesis have substantial implications for OSM and our current understanding of object processing failures more generally. These implications largely surround the role played by distractors in OSM and, by extension, the relationship – hitherto uninvestigated – between OSM and crowding. However, there were limits to the paradigms used in the current thesis and thus there are a number of aspects of the phenomenon and specifically the OSM×crowding interaction that require further investigation. These avenues for future research will now be discussed.

5.11.1 The hallmarks of crowding

The key finding of this thesis was that crowding (as opposed to set size) interacted with OSM. There are a number of features of this interaction that require further investigation. One clear point of interest relates to how the interaction conforms to some of the hallmarks of OSM and crowding. Both OSM and crowding have a number of hallmarks which are argued to characterise and define the phenomena. This thesis started to explore this in Experiment 10 by examining whether the effect scaled with eccentricity. However, the results of this study were somewhat inconclusive and could therefore be a starting point for the continued investigation in regards to the hallmarks of crowding as discussed in section 5.9. From this point there are a number of other hallmarks that warrant investigation in relation to this interaction between OSM and crowding. These include the role of "pop out", the anisotropic profile and the differential effects of crowding and OSM on detection and identification tasks.

The role of "pop out" in OSM and crowding

The results of this thesis have shown that distractors are indeed important in OSM. However, this role of distractors is not in the way that was originally suggested by Di Lollo and colleagues (2000) relating to "time to contact" of spatial attention. Rather, the role of distractors in OSM relates to the fact that they produce crowding. A key aspect of both OSM and crowding is that they are strongly affected by target distinctiveness: both OSM and crowding become attenuated when the target "pops out" from the display (Bernard & Chung, 2011; Chung et al., 2001; Hariharan et al., 2005; Kooi et al., 1994; Lleras & Moore, 2003; Moore & Lleras, 2005). It is conceivable therefore that the role of "pop out" in OSM could represent a release from crowding, at least to a certain extent. This is something itself that requires further investigation.

Another point of interest however is the fact that there are seeming differences in the effect of "pop out" in crowding and OSM. For instance Gellatly et al (2006) produced a release from OSM, but this effect occurred mainly for the feature dimension on which the target "pop out" occurred.

Specifically, when the "pop out" feature was the target colour, reporting of the colour was insensitive to masking. However, reporting of the orientation of that same target was still substantially affected by masking. With crowding in contrast, having the target "pop out" on any feature dimension seems to reduce crowding. For instance, when the target is presented in red and the flankers are presented in black, crowding is effectively eliminated. This is regardless of the fact that the task is to identify the shape of the target (e.g. Põder, 2007).

It is worth noting that in the Gellatly et al (2006) study the "pop out" of the target from the distractors was conflated with "pop out" from the mask (both mask and distractors were composed of the same elements). The intention of this experiment was to explore feature binding rather than "pop out" per se suggesting that a systematic investigation of "pop out" effects in OSM is still required. From this point, the influence of "pop out" on the crowding×OSM interaction could be explored.

The role of "pop out" could be easily investigated within the paradigm used in this thesis, for example a red target digit could be presented within the context of a display array containing three black digit distractors. It would be expected that the distinctiveness of the target would lead to reduced crowding at the small target-flanker distances. What is of interest however is how "pop out" would influence the interaction between OSM and crowding. That is, the main focus would be whether "pop out" of the target has any influence at the medium target-flanker distance under conditions of OSM i.e. whether "pop out" would reduce or eliminate the inverted U-shaped function of the interaction between OSM and crowding that has been found in this thesis.

The anisotropic profile of crowding

Another hallmark of crowding is that it has an anisotropic profile. Specifically, radially positioned flankers produce more effective crowding than tangentially positioned flankers (Bouma, 1970; Toet & Levi, 1992; Whitney & Levi, 2011). This element of crowding was not specifically utilised in the experiments presented in this thesis. Given that the stimuli were presented on a circumferential display in the experiments in this thesis the target and the surrounding distractors were presented diagonally from one another rather than radially (Toet & Levi, 1992).

If the interaction between OSM and crowding is indeed a parallel to that of "supercrowding" (Vickery et al., 2009), it should present with the hallmarks of crowding as "supercrowding" does. If this is the case then it would be expected that the magnitude of OSM would change based on this anisotropic profile. That is, the magnitude of OSM and the distance over which crowding is effective should increase with radial display presentation.

As such, in order to explore the relationship between crowding and OSM it might be beneficial conducting experiments which are more like classical crowding experiments. That is, where the flankers are arranged around the target rather than being on a notional circle as in the paradigm used in this thesis. This would greatly simplify the investigation of the relationship between crowding and OSM. The current experiments were inspired by the way in which many experiments on OSM have been conducted previously. As such, these experiments followed the tradition of OSM rather than that of crowding. Using a standard crowding paradigm could therefore allow a fuller investigation of the effect of OSM, and its relation to crowding.

The effects of crowding and OSM on target detection and identification

A further hallmark of crowding is that it is argued to have a dissociable effect on target detection and identification tasks i.e. crowding is argued to have little impact on target detection (e.g. Freeman & Pelli, 2007; Andriessen & Bouma, 1976; Wilkinson et al., 1997). The second experiment in this thesis found an effect of set size on target detection. The effect of set size produced in Chapter 2 was later attributed to crowding. Thus, this experiment may be an indication of crowding impacting a target detection task. It may be therefore that the "supercrowding" effect is different in its capacity to affect target detection than traditional crowding. Given the fact that this effect on detection was found when examining the effect of set size it cannot be unequivocally stated that this effect is related to the "supercrowding" found in Chapter 3.

Thus, there is still an outstanding question regarding the nature of what happens to the stimulus under conditions of OSM and crowding. That is, whether OSM and crowding have equivalent or different effects in terms of their impairment on target perceptibility. Crowding is argued to represent a "muddling" or "blurring" of the target representation in which the extent of the degradation of the target percept can vary (Parkes et al., 2001). OSM by contrast is claimed to be an all or none phenomenon in which either the target is perceived or it is not (Di Lollo et al., 2000). The very suggestion of an object *substitution* process is indicative of one in which the affected object is obliterated from perception rather than merely degraded.

These differences in terms of the nature of the processing impairment which ensues also correspond with the differences in the types of judgement which are affected by the two phenomena. That is, the fact that OSM reliably affects target detection (as in Experiment 3 of this thesis) can be seen as a consequence of its all-or-non nature in preventing awareness of the target. Similarly the limited effect of crowding on detection can be seen as a consequence of the fact that crowding "muddles" the target percept i.e. reduces the discriminability of the individual target features, but does not affect the detection of the target as a whole.

Research is being conducted in the crowding field with the aim of elucidating exactly what happens to the target percept under conditions of crowding. A number of methods have been used, for instance investigating positional uncertainty (i.e. exploring misplacement of the target position within a partial report paradigm; Zhang, Zhang, Liu & Yu, 2012), and by requiring observers to attempt to draw the stimulus under conditions of crowding (Coates, Wagemans & Sayim, 2015). This suggests that similar work needs to be undertaken with OSM to understand if the phenomenal consequences of the phenomena are similar or different (i.e. whether masking does in fact lead to a complete loss of the target percept while crowding causes a muddled percept of the target).

The interaction between masking and crowding

A further question relates to whether the effect of OSM is different to other forms of masking in terms of the extent to which they interact with crowding. That is, it is unclear whether there is something particularly special about the effect of OSM on crowding compared to the effect that low level, surround and pattern masks have been found to have on crowding previously (Vickery et al., 2009). It is feasible that the effect of OSM is likely to be different from the types of masking found to interact with crowding previously given the arguably higher-level nature of OSM. It would therefore be worth investigating the effects of these different forms of masking on crowding within the same experiment in an attempt to understand if they do in fact differ in their effect on crowding.

Research by Chakravarthi and Cavanagh (2009) has to some extent examined this. They examined the extent to which pattern, metacontrast and four dot masks [OSM] could reduce crowding when they masked the flankers. It was found that pattern and metacontrast masks were able to prevent crowding while OSM had no effect on target crowding. However as discussed in sections 3.1.6 and5.7, the paradigm used by Chakravarthi and Cavanagh was markedly different from that used in this thesis. Moreover, there are potential confounds in the Chakravarthi and Cavanagh study which meant that OSM could have had a somewhat facilitatory effect on crowding, rather than reducing it (see section 5.7). It might therefore be beneficial to include these paradigms within the same experiment.

This experiment would include the target and flankers and would systematically vary the masking of the target and the flankers. The study by Chakravarthi & Cavanagh (2009) only varied the masking of the flankers. The studies presented in this thesis varied only the target masking, and used only OSM. By systematically varying both the target and flanker masking using the three different types of mask, it would provide a better sense of how to reconcile the current results from those of Chakravarthi & Cavanagh. It would also provide evidence as to whether the effect of OSM on crowding is actually functionally different to that of other forms of masking, ones which are reliant on lower-level contour interactions.

5.11.2 Electrophysiological investigation of the role of OSM in crowding

The final component of this thesis that requires further investigation is the nature of the interaction between OSM and crowding in terms of the underlying electrophysiology. The *P1* and *N1* components were chosen to investigate the interaction between OSM and crowding in Experiment 11 as these components have been used to investigate both OSM and crowding previously (Chicherov et al., 2014; Harris et al., 2013; Wynn et al., 2013). In hindsight perhaps, these components were arguably too early occurring to assess the interaction between OSM and crowding as neither of these phenomena were found to have an effect on either P1 or N1 amplitude. As such, the examination of higher level ERP components is needed to evaluate the interaction between OSM and crowding. There are a number of ways in which the electrophysiological examination of OSM could be investigated in future studies. These potential ERP studies will now be discussed.

Firstly, the ERP paradigm used in Experiment 11 just investigated the overall brain response to the stimulus array. This meant that the responses were a conflation of the ERP effects associated with processing of the target with those associated with processing of the distractors (which in the paradigm onset at the same time). This may have diluted the possibility of finding any effects related to target processing. This issue, as noted earlier, affected interpretation of the *N1* amplitude in this experiment as it cannot be revealed whether the observed changes in *N1* amplitude are specifically related to changes in target processing, distractor processing, or some general attentional process associated with the spatial spread of the display items. The difficulty is that components such as the *P1* and *N1* are largely non-specific ones in that they reflect the amalgamated processing of stimuli across the visual field associated with a particular epoch (Luck, 2014).

There are other ERP components which can, with the appropriate experimental design, be more easily attributed to target processing alone. Two such components that could be used in this way are the *N2pc* and N170. The *N2pc* in particular is a component that seems to be more directly associated with selective attentional processes.

The *N2pc* is a lateralised ERP component associated with attentional selection of a target in the contralateral visual field. Because of this, the display is required to be balanced across the two hemifields. This is so that the display is perceptually symmetrical and the target in each trial is defined by something which is only determinable by task instructions (e.g. a red and green item is presented respectively to the two visual fields, the left and right position varying across trials; the task is to report the red item on some trials and the green one on others).

Implementation of this type of paradigm would therefore require substantial modifications to the presentation given in Experiment 11. The current circumferential displays could be retained. However, rather than having a single possible target (i.e. a single item surrounded by four dots) as in all the current experiments there would have to be two possible targets, one in each hemifield. The 4DMs surrounding the possible targets could be different colours (e.g. red and blue); the lateral position of the red and blue 4DM would vary randomly across trials. The *N2pc* paradigm has a distinct advantage over the paradigm used in the last chapter. In analysing the *N2pc* it enables the investigation of the separable electrophysiological effects for distractors and the deployment of selective attention related to the target (since the analysis is performed in terms of the electrodes relative to the on-screen lateral position of the target).

The *N2pc* has been investigated in relation to OSM by two previous papers (Prime et al., 2011; Woodman & Luck, 2003). Both of these studies report that the *N2pc* component remains intact under conditions of OSM. In contrast, recent research in the crowding literature has found that crowding results in a decline in *N2pc* amplitude (Anderson, Ester, Klee, Vogel & Awh, 2014). This component could therefore prove to be a way of elucidating the "supercrowding" effect in terms of an electrophysiological measure that distinguishes the role of crowding and OSM. The problem is that there is still little electrophysiological research on either OSM or crowding. As such, it is unclear how reliable these effects are and how useful the *N2pc* paradigm would prove to be in understanding the interaction between crowding and OSM.

A second potential way of investigating the attentional involvement in this interaction is by focusing on the *N170* component. With the appropriate experimental design the *N170* could be used to focus on the neural response to a target item under masking and crowding conditions. The *N170* is a face-selective ERP associated with visual processing; it is argued to represent focal attentional categorisation processes (Eimer, Holmes, & McGlone, 2003; Rousselet, Macé & Fabre-Thorpe, 2004). The

N170's most characteristic feature is that it presents increased negative amplitude for face stimuli when compared with a baseline condition for non-face-stimuli (Axelrod, Bar & Rees, 2015).

There is potential for the *N170* to be assessed with the sorts of displays used in this thesis. However different stimulus types would be necessary in order to evoke an N170. As such the experiments would necessarily constitute something of a large departure from the sorts of experiments in this thesis. The current digit stimuli could be replaced with different types of face stimuli for example. The task for instance could be to report some form of classification judgement of the face stimulus (e.g. whether the face was male or female, old or young etc.).

In order to produce any magnitude of crowding, distractors would have to be visually similar in form to the target face without being faces themselves (otherwise the paradigm would suffer from the same problem of being unable to distinguish between the neural response to the target and that of the distractors). In crowding experiments non-face flankers which themselves are perceptually similar to faces in terms of their feature properties but which are not perceived as faces have been used (e.g. Faivre, Berthet & Kouider., 2012). These stimuli would consequently not evoke an *N170*. Interestingly the *N170* has been shown to be suppressed under OSM (Axelrod et al., 2015; Harris et al., 2013). With an appropriately designed study of the kind indicated above, the extent to which an *N170* was observed might serve as a neural correlate of the interaction between crowding and OSM and in doing so indicate something of the time course in which the interaction occurs.

5.12 Conclusions

OSM has continued to be of research interest since Di Lollo and colleagues' original description of the phenomenon in 2000. Indeed, an academic search reveals that 128 articles have been published since Di Lollo and colleagues' (2000) original paper referring specifically to "Object substitution masking" or "Common onset masking" in the title. This is potentially because OSM is argued to provide a novel insight into the spatiotemporal dynamics of visual attention and perception.

The initial, and most widely held neurocognitive theory of OSM to date, the OSTM, claims that the object based interactions that occur between the target and mask involve re-entrant processing between high and low level visual areas. That is, OSM is postulated to occur because of a mismatch between the existing information (target+mask) and the ongoing signal (mask alone) when the mask trails the target. A major component in this OSTM model is spatial attention. Spatial attention is deemed to be crucial in determining the speed with which a successful re-entrant match can be obtained with resultant conscious perception of the target. OSM has been argued to occur only under conditions where attention cannot be quickly focused on the target, for example with large set size displays. As such, set size is considered to be a vital component of the OSM paradigm according to the OSTM.

The findings of the present thesis showed in contrast that set size does not in fact modulate OSM, at least not in any direct way. Rather, it was shown that this effect of set size is actually the consequence of crowding of the target, a possibility noted in Di Lollo et al's (2000) original paper but never actually explored in their experiment, nor in any published empirical study since then. It was found that when set size and crowding were separated from one another as factors of influence crowding increased the magnitude of OSM whereas set size had an effect on overall performance without affecting OSM. These findings therefore raise questions over the current instantiation of the OSTM. That is, attentional modulation as expressed with set size is not an appropriate explanation for OSM.

What is currently unclear is whether the interaction between crowding and OSM requires attentional involvement. That is, crowding is traditionally viewed as a low level processing impairment whereas OSM is deemed a high level processing impairment. As such, it is unclear at which stage these phenomena interact. The electrophysiological data presented in this thesis were inconclusive in providing information on this factor. However, the fact that there was no effect of the interaction between OSM and crowding on early visual components suggests that perhaps there is an attentional involvement in this effect.

Finally, the interaction between OSM and crowding found in this thesis was revealed as an inverted U-shaped function on performance. That is, the effect of OSM was greatest at medium target-flanker distances arguably representing an effect of OSM on crowding rather than an effect of crowding on OSM as was originally expected. Specifically, it appears that OSM was able to increase the distance with which flankers crowded the target. Consequently, these findings show parallels with that of "supercrowding".

The fact that OSM potentially impacts crowding has implications for the current proposed iteration of the object processing hierarchy. Crowding is currently placed earlier in the object processing hierarchy than OSM. OSM would be unable to affect crowding if they fell within these strict levels of object processing as crowding of the target would have already taken place prior to OSM occurring. Thus, these findings indicate that the current instantiation of the object processing hierarchy does not fully explain the processing impairments that occur with these phenomena.

Another possible explanation is that visual object processing cannot be explained within a strict hierarchy, at least in the form recently proposed by Breitmeyer (2014). This seems particularly likely given the involvement of re-entrant processing in visual object processing. These findings therefore not only have implications for our current understanding of OSM but also the current understanding of the object processing hierarchy. This in turn has implications for the way in which we understand how visual processing leads to the emergence of a conscious percept and how the particular stimulus conditions can lead to a failure of this conscious percept to emerge.

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Appendices

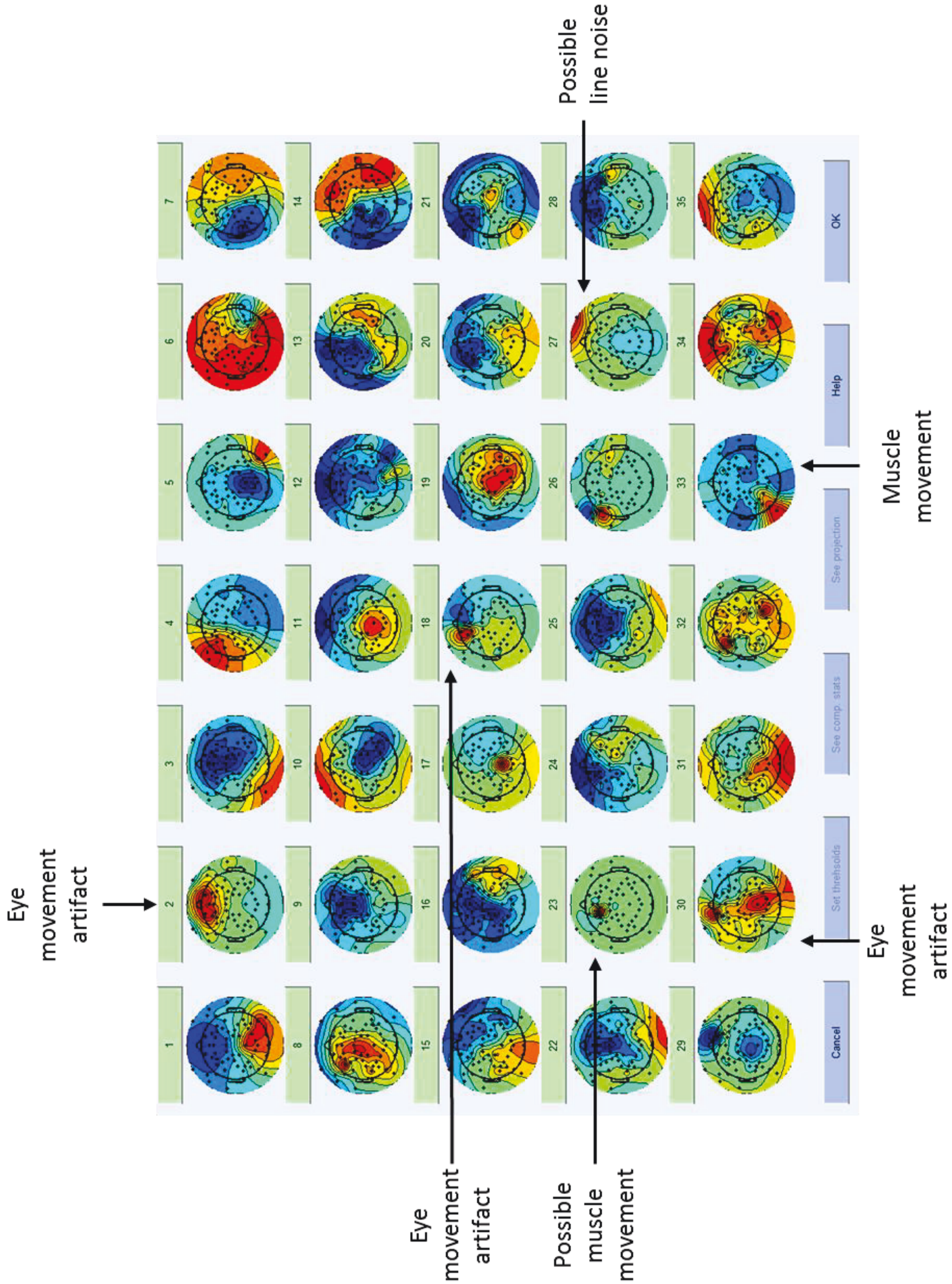
Appendix A: ICA decompositions for artifact rejection

Appendix B: Electrophysiological statistics results tables

Appendix C: Ethics committee approvals

Appendix D: Published paper

Appendix A: ICA decompositions for artifact rejection



Appendix B: Electrophysiological statistics results tables

Table 1| The ANOVA analysis for the mean positive amplitude for each individual electrode.

	F	MS_{error}	*p*
E30 Electrode			
Masking	0.07	0.07	.795
Crowding	1.47	0.07	.252
Interaction	1.30	0.08	.294
E31 Electrode			
Masking	3.75	0.06	.079
Crowding	0.18	0.16	.839
Interaction	1.87	0.12	.177
E32 Electrode			
Masking	0.11	0.08	.748
Crowding	3.80	0.06	.065
Interaction	1.78	0.06	.193
E33 Electrode			
Masking	0.39	0.09	.546
Crowding	0.43	0.25	.654
Interaction	0.52	0.12	.601
E35 Electrode			
Masking	0.08	0.08	.789
Crowding	1.18	0.14	.327
Interaction	1.13	0.10	.342
E38 Electrode			
Masking	<0.01	0.13	.998
Crowding	0.62	0.33	.547
Interaction	0.87	0.14	.434
E39 Electrode			
Masking	0.26	0.11	.622
Crowding	0.29	0.25	.750
Interaction	1.27	0.17	.302
E40 Electrode			

Masking	0.18	0.08	.678
Crowding	0.82	0.24	.455
Interaction	0.36	0.12	.705
E43 Electrode			
Masking	0.86	0.10	.375
Crowding	0.10	0.08	.908
Interaction	1.99	0.07	.160
E44 Electrode			
Masking	0.08	0.18	.783
Crowding	0.20	0.22	.730
Interaction	1.08	0.11	.356

Table 2| The ANOVA analysis for the mean positive amplitude for each individual electrode for correct vs. incorrect performance.

	F	MS_{error}	*p*
E30 Electrode			
Correct vs. incorrect performance	1.10	0.21	.316
Masking	0.23	0.33	.644
Crowding	2.28	0.46	.152
PerformancexMasking	0.75	0.24	.404
PerformancexCrowding	1.13	0.59	.326
MaskingxCrowding	0.10	0.15	.901
Three-way interaction	1.69	0.30	.208
E31 Electrode			
Correct vs. incorrect	3.07	0.48	.108
Masking	0.12	0.25	.731
Crowding	0.45	0.49	.644
PerformancexMasking	0.88	0.39	.369
PerformancexCrowding	1.29	0.83	.284
MaskingxCrowding	0.17	0.28	.847
Three-way interaction	1.26	0.74	.206

E32 Electrode			
Correct vs. incorrect	0.59	0.20	.469
Masking	<0.01	0.19	.477
Crowding	0.20	0.27	.823
PerformancexMasking	0.04	0.34	.854
PerformancexCrowding	0.36	0.76	.588
MaskingxCrowding	0.05	0.14	.948
Three-way interaction	2.75	0.27	.098
E33 Electrode			
Correct vs. incorrect	1.74	0.64	.214
Masking	0.06	0.32	.819
Crowding	0.33	0.64	.725
PerformancexMasking	0.76	0.77	.480
PerformancexCrowding	0.45	0.08	.646
MaskingxCrowding	0.14	0.22	.868
Three-way interaction	3.08	0.23	.066
E35 Electrode			
Correct vs. incorrect	0.68	0.31	.427
Masking	0.32	0.27	.584
Crowding	1.69	0.33	.207
PerformancexMasking	0.08	0.21	.779
PerformancexCrowding	1.04	0.36	.371
MaskingxCrowding	0.24	0.16	.786
Three-way interaction	2.44	0.30	.111
E38 Electrode			
Correct vs. incorrect	0.98	1.04	.343
Masking	0.25	0.34	.625
Crowding	0.77	0.84	.771
PerformancexMasking	0.07	0.48	.792
PerformancexCrowding	0.38	1.23	.690
MaskingxCrowding	0.66	0.28	.525
Three-way interaction	2.02	0.41	.157
E39 Electrode			
Correct vs. incorrect	0.04	2.42	.848
Masking	0.98	0.58	.346

Crowding	0.65	1.00	.533
PerformancexMasking	<0.01	0.53	.993
PerformancexCrowding	0.49	1.05	.623
MaskingxCrowding	0.95	0.63	.409
Three-way interaction	3.21	0.63	.067
E40 Electrode			
Correct vs. incorrect	0.22	2.29	.649
Masking	0.29	0.48	.607
Crowding	1.70	0.48	.211
PerformancexMasking	0.26	0.84	.625
PerformancexCrowding	0.45	1.76	.644
MaskingxCrowding	0.29	0.84	.753
Three-way interaction	1.79	1.09	.212
E43 Electrode			
Correct vs. incorrect	0.46	0.59	.514
Masking	0.21	0.26	.655
Crowding	1.02	0.18	.380
PerformancexMasking	0.86	0.11	.376
PerformancexCrowding	0.78	0.88	.418
MaskingxCrowding	0.20	0.18	.820
Three-way interaction	2.02	0.35	.159
E44 Electrode			
Correct vs. incorrect	0.77	1.88	.409
Masking	0.22	0.28	.657
Crowding	1.68	0.14	.22
PerformancexMasking	0.04	0.11	.849
PerformancexCrowding	0.37	3.39	.569
MaskingxCrowding	0.52	0.65	.604
Three-way interaction	1.22	0.67	.324

Table 3| The ANOVA analysis for the mean negative amplitude for each individual electrode.

	F	MS^{error}	p
E30 Electrode			
Masking	0.05	0.07	.836
Crowding	3.06	0.07	.067
Interaction	0.03	0.11	.968
E31 Electrode			
Masking	0.01	0.14	.910
Crowding	3.27	0.07	.057
Interaction	0.58	0.09	.571
E32 Electrode			
Masking	0.23	0.09	.644
Crowding	5.57	0.04	.011
Interaction	0.39	0.07	.680
E33 Electrode			
Masking	0.36	0.18	.559
Crowding	4.91	0.12	.017
Interaction	0.11	0.10	.900
E35 Electrode			
Masking	1.17	0.11	.303
Crowding	6.95	0.10	.005
Interaction	0.77	0.11	.474
E38 Electrode			
Masking	0.61	0.24	.450
Crowding	1.75	0.21	.197
Interaction	0.94	0.19	.408
E39 Electrode			
Masking	2.45	0.16	.146
Crowding	0.48	0.34	.628
Interaction	2.09	0.19	.147
E40 Electrode			
Masking	0.03	0.26	.874
Crowding	1.57	0.16	.230
Interaction	0.70	0.16	.508

E43 Electrode			
Masking	1.60	0.07	.221
Crowding	0.68	0.07	.517
Interaction	1.76	0.11	.196
E44 Electrode			
Masking	0.48	0.16	.504
Crowding	0.61	0.11	.553
Interaction	1.93	0.10	.168

Table 4| The ANOVA analysis for the mean negative amplitude for each individual electrode for correct vs. incorrect performance.

	F	MS_{error}	*p*
E30 Electrode			
Correct vs. incorrect performance	1.11	0.28	.301
Masking	0.10	0.18	.758
Crowding	4.43	0.19	.024
PerformancexMasking	1.10	0.24	.317
PerformancexCrowding	3.63	0.29	.043
MaskingxCrowding	0.95	0.40	.950
Three-way interaction	.44	0.34	.651
E31 Electrode			
Correct vs. incorrect	2.62	0.71	.134
Masking	0.11	0.44	.752
Crowding	4.98	0.34	.016
PerformancexMasking	0.33	0.34	.579
PerformancexCrowding	4.59	0.29	.022
MaskingxCrowding	0.44	0.59	.652
Three-way interaction	0.37	0.71	.697

E32 Electrode			
Correct vs. incorrect	0.42	0.19	.532
Masking	0.07	0.18	.797
Crowding	4.25	0.16	.027
PerformancexMasking	0.82	0.17	.385
PerformancexCrowding	2.64	0.29	.094
MaskingxCrowding	0.22	0.17	.806
Three-way interaction	1.77	0.16	.193
E33 Electrode			
Correct vs. incorrect	1.99	0.85	.186
Masking	0.36	0.62	.558
Crowding	6.01	0.25	.008
PerformancexMasking	0.28	0.54	.608
PerformancexCrowding	3.01	0.34	.070
MaskingxCrowding	0.60	0.38	.559
Three-way interaction	0.75	0.64	.483
E35 Electrode			
Correct vs. incorrect	0.70	0.47	.420
Masking	0.49	0.45	.497
Crowding	10.26	0.19	.001
PerformancexMasking	0.25	0.43	.624
PerformancexCrowding	2.12	0.39	.144
MaskingxCrowding	1.63	0.21	.219
Three-way interaction	1.02	0.28	.376
E38 Electrode			
Correct vs. incorrect	1.65	1.11	.226
Masking	0.61	0.78	.453
Crowding	2.22	0.43	.132
PerformancexMasking	1.25	0.50	.288
PerformancexCrowding	1.65	0.32	.216
MaskingxCrowding	2.25	0.45	.129
Three-way interaction	0.79	0.57	.468
E39 Electrode			
Correct vs. incorrect	0.53	0.58	.481
Masking	1.80	0.53	.207

Crowding	0.39	1.41	.599
PerformancexMasking	1.10	0.38	.318
PerformancexCrowding	1.03	0.35	.373
MaskingxCrowding	4.19	0.47	.029
Three-way interaction	2.11	0.62	.145
E40 Electrode			
Correct vs. incorrect	2.91	0.68	.116
Masking	0.04	0.77	.845
Crowding	1.82	0.35	.186
PerformancexMasking	0.51	0.34	.492
PerformancexCrowding	0.62	0.26	.549
MaskingxCrowding	1.77	0.31	.194
Three-way interaction	0.79	0.42	.466
E43 Electrode			
Correct vs. incorrect			
Masking	0.03	0.13	.861
Crowding	1.52	0.11	.243
PerformancexMasking	0.80	0.19	.461
PerformancexCrowding	0.44	0.07	.521
MaskingxCrowding	0.05	0.16	.952
Three-way interaction	2.25	0.22	.129
E44 Electrode			
Correct vs. incorrect	0.29	0.34	.604
Masking	0.64	0.26	.442
Crowding	0.51	0.31	.610
PerformancexMasking	0.35	0.16	.564
PerformancexCrowding	<0.01	0.18	.998
MaskingxCrowding	2.04	0.22	.154
Three-way interaction	8.17	0.06	.002

Appendix C: Ethics committee approval

Appendix D: Published paper

Camp, S., Pilling, M., Argyropoulos, I & Gellatly, A. (2015). The role of distractors in Object Substitution Masking. *Journal of Experimental Psychology: Human Perception and Performance, 41(4)*, 940-957.