Selective Attention and Inhibition: Effects of Inhibition Tasks on Subsequent Distractor Rejection

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Abstract

Recent work has shown that the extent to which irrelevant distractors are perceived is determined by the level of perceptual load in relevant processing. While high perceptual load typically reduces distractor perception, low perceptual load typically results in perception of irrelevant distractors (see Lavie, 2001 for review). Thus in situations of low perceptual load, response tendencies toward the perceived yet irrelevant distractors must be prevented from leading to unwanted responses. This thesis provides a new line of behavioural evidence for the suggestion that selective attention involves inhibition of response tendencies to perceived distractors in situations of low perceptual load. Specifically, the present studies examined whether engaging response inhibition in one task would lead to greater response competition effects from irrelevant distractors on responses in a subsequent flanker task. We designed a new paradigm in which a flanker task was preceded by a response inhibition task on each trial. Response inhibition was manipulated either by varying the demand to make a response or to stop it (using a stop signal task – Chapter 2); or by varying the spatial congruency of the mapping between stimuli and responses (Chapter 3); or by varying the congruency between relevant and irrelevant dimensions in a Stroop colour word task (Chapter 4). The results suggest that the engagement of inhibition in the first task of each trial reduces the efficiency with which response tendencies to distractors were suppressed in the following flanker task. Carry-over effects of inhibition were dissociated from the effects of the general difficulty of Task 1; were found to persist across an interval of several seconds between the first and second tasks; and were also found to occur only in situations of low perceptual load. These findings thus provide new support for the suggestion that active inhibition is involved in selective attention.

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CHAPTER ONE

General Introduction

Preface

Selective attention allows people to conduct their mental processes and behaviour on the basis of information that is relevant to their goals. In this thesis, I argue that such goal-directed control of behaviour has, under some circumstances, to involve suppression of responses to distractors that have been perceived despite their irrelevancy.

Lavie and colleagues have demonstrated that in some situations selective attention permits the exclusion of distractors from perception (e.g. Lavie, 1995; Lavie & Cox, 1997; for review see Lavie, 2000). When the perceptual load of the relevant stimuli in a task is high enough to exhaust perceptual capacity, then distractors are not perceived simply by virtue of there not being enough capacity for their perception. However, Lavie's studies have also shown that in situations of low perceptual load, irrelevant distractors are consistently perceived regardless of subjects' intention to ignore them. For goal-directed action in situations of low perceptual load, where distractors are unavoidably perceived and identified, tendencies to respond to these distractors require active suppression. In the present thesis I examine this claim in a series of experiments that assess the extent to which efficiency of distractor rejection in selective attention tasks depends on whether inhibition was engaged in a preceding task. The rationale for this design is that if rejection of perceived distractors under situations of low perceptual load requires inhibition then a greater distractor interference effect should be found when inhibition mechanisms are engaged in another task and are thus unavailable for response suppression in the selective attention task.

In this chapter I discuss how the literature on selective attention suggests a role for inhibition in the rejection of irrelevant distractors. The existing evidence for such processes of distractor inhibition is then discussed and the shortcomings of this evidence are highlighted. I then proceed to consider what type of inhibition task may engage similar processes of inhibition to those needed for suppression of responses to distractors in selective attention tasks, and I describe the tasks that were used in this thesis to investigate the role of inhibition in distractor processing.

Selective attention: circumstances under which inhibition of irrelevant distractors is necessary

The early/late selection debate

This thesis is concerned with the mechanisms of rejection of irrelevant distractors that were perceived in selective attention tasks despite their task-irrelevancy. For many years research on selective attention focused on the question of whether irrelevant distractors are excluded only from responses (late selection, e.g. Duncan, 1980), or can also be excluded from early perceptual processing (early selection, e.g. Treisman, 1964). Early selection theorists propose that selection of relevant stimuli occurs on the basis of physical features, at a stage in processing prior to the identification of stimuli. Thus, on an early selection account, unattended stimuli do not undergo full perception and identification (Broadbent, 1958; Shiffrin, 1976; Francolini & Egeth, 1980; Kahneman & Henik, 1981; Treisman, 1964; Yantis & Johnston, 1990). On the other hand, the central proposal of late selection theory is that all items in the visual field, both relevant and irrelevant, are perceived and identified. On this account, only after identification are the relevant items then selected for further processes such as response production (e.g. Deutsch & Deutsch, 1963; Allport, 1977; Duncan, 1980; Miller, 1981; Tipper & Driver, 1988). Over decades of research, compelling evidence has accumulated in support of early selection views and late selection views.

Much of the empirical evidence bearing on this debate comes from the flanker paradigm. In this paradigm subjects are required to identify a target letter while ignoring one or more distractor letters. RTs in this task are increased when the target and distractors are members of different response categories, compared to when they belong to the same category or when the distractor is not associated with a response (Eriksen & Eriksen, 1974). The flanker task has provided evidence for both early and late selection views. Early studies provided support for the late selection position, as they showed interference from task-irrelevant information, indicating that this irrelevant information had been identified. However, some researchers have suggested that irrelevant information only intrudes on processing when the task is not optimally configured for attentional focus. For instance, studies manipulating the distance between targets and distractor have suggested that a clear separation between relevant and irrelevant items is necessary for early selection to take place (Eriksen & Hoffman, 1972, 1973; Eriksen & St. James, 1986; Johnston & Dark, 1986; Yantis & Johnston, 1990). Indeed, increases in separation between relevant and irrelevant items have been shown to virtually eliminate interference in the flanker paradigm (Yantis & Johnston, 1990; Paquet & Craig, 1997). However, while clear separation may be necessary, it is not sufficient for early selection, as is shown by findings of interference from clearly separated distractors (e.g. Eriksen &

Eriksen, 1974; Miller, 1987; Gatti & Egeth, 1978; Hagenaar & van der Heijden, 1986; Kahneman & Henik, 1981).

Evidence favouring either side of the early/late selection debate has also been produced using measures of semantic priming from ignored words. On an early selection account, if a word is presented in an unattended location, it will not be identified, and thus should not lead to semantic priming. This assertion has been supported by findings of semantic priming being eliminated when attention is directed away from the prime word (Paap & Newsome, 1981; Dark, Johnston, Myles-Worsley & Farah, 1985; Johnston & Dark, 1985). However, as with the flanker paradigm, other studies have found intact semantic priming from words in unattended locations, even with clear spatial separation between relevant and irrelevant items, providing support for a late selection view (Hoffman & MacMillan, 1985; Lambert, Beard & Thompson, 1988; Underwood, Rusted, Thwaites, 1983; Underwood & Thwaites, 1982).

The phenomenon of negative priming (NP), referring to increased RTs to targets that were previously presented as irrelevant distractors, was initially interpreted as a new line of support for the late selection position (Tipper, 1985; Tipper & Cranston, 1985). The finding that NP is observed when the target item is not identical to, but a semantic associate of, the distractor in the previous trial was taken to indicate that unattended items are processed to semantic levels (Tipper & Driver, 1988). Strong support for late selection was produced in a study by Driver & Tipper (1989). Whereas Francolini & Egeth (1980) observed no interference from an unattended item in a Stroop-like task, Driver & Tipper (1989) observed NP from unattended items in an identical task when they appeared as targets in the following trial. This result suggests that a lack of concurrent interference from a distractor does not imply a lack of processing of that distractor, and thus the NP provides evidence for late selection from within a situation that had previously provided evidence for early selection.

However, other NP studies have provided evidence in favour of early selection: Ruthruff & Miller (1995) found that irrelevant distractors produced neither interference nor NP when target and distractor positions remained constant within a block, thus allowing more efficient focusing of attention. Paquet (2001) found that neither concurrent interference or NP were produced when the target position was pre-cued and clearly separated from the distractors.

Hybrid theories of selective attention

Given the wealth of evidence accumulated on both sides of the early/late selection debate, it seems that any successful model of selective attention will need to account for findings of both early and late selection. Indeed, several studies have demonstrated both early and late selection occurring depending on the characteristics of the task (Johnston, McCann & Remington, 1995; Yantis & Johnston, 1990; Paquet & Lortie, 1990). However, these theories do not make clear *which* characteristics of a task situation determine the locus of selection. Potential candidates such as target-distractor separation (Eriksen & Hoffman, 1972; Hagenaar & van der Heijden, 1986), distractor category relevance (Paquet & Lortie, 1990; Miller, 1987), and other means of optimising attentional focus have all produced equivocal results.

A hybrid model suggested by Lavie (1995; Lavie & Tsal, 1994) implicates the *perceptual load* of the task as the factor determining the locus of selection. Lavie proposed that perception is a limited capacity process which proceeds automatically until its capacity is exhausted. If the relevant information in a display is characterised by a high enough level of perceptual load, this information will exhaust perceptual capacity by itself, leaving none for the perception of irrelevant information. If, on the other hand, there is low perceptual load in the relevant information, excess perceptual capacity will automatically be applied to any irrelevant information present. Thus, the perception of *irrelevant* information, and thus the locus of selection, depends on the perceptual load of the *relevant* information: with high load, early selection occurs, and with low load, late selection is necessary.

Empirical support for this model is provided by studies using varied manipulations of perceptual load and different measures of irrelevant processing. Lavie (1995) and Lavie & Cox (1997) manipulated perceptual load in the relevant processing via the relevant search set size, and by the target-non-target similarity. Both studies showed that response competition effects from irrelevant distractors outside the search set were reduced in high (large set size/similar target and non-target) vs. low (small set size/dissimilar target and non-target) perceptual load situations. Lavie (1995) also manipulated the perceptual load of a task without altering the stimuli by varying the processing requirements on those stimuli. She observed reduced distractor effects when subjects performed a discrimination task requiring identification of a conjunction of features (high load) vs. a simple feature identification task (low load) on the relevant stimuli (a definition of perceptual load provided by Feature Integration Theory, Treisman & Gelade, 1980). Likewise, she observed a reduction in distractor effects when subjects performed a fine shape discrimination task (high load) vs. a simple absent-versus-present detection task (low load – see Bonnel, Possamai & Schmitt, 1987; Uttal, 1987; Graham, 1989). Using NP as a measure of irrelevant processing, Lavie & Fox (2000) demonstrated that NP as well as concurrent interference from prime distractors is reduced when the perceptual load of the relevant task in the prime is increased. Also, a reduction in distractor processing has been demonstrated at the neural level in a PET study by Rees, Frith & Lavie (1997), showing that the neural response to irrelevant motion is attenuated when subjects discriminate the number of syllables in a word (high load) vs. when they simply discriminate whether the word was presented in upper or lower case type (low load).

Recently, Handy & Mangun (2000) provided evidence from an ERP study that perceptual load influences the allocation of attentional resources at an early stage in visual processing. The sensory-evoked P1 and N1 ERP components (which arise 100 and 200 ms after stimulus onset respectively) have been shown to increase in amplitude with the amount of attentional resources allocated to the location of the ERP-eliciting stimulus (Mangun & Hillyard, 1990). Handy & Mangun (2000) demonstrated that these effects of allocating attention to the target location were reduced when subjects performed a difficult discrimination (high perceptual load) vs. an easier discrimination (low perceptual load). Thus, ERP components which are sensitive to the allocation of attentional resources at an early stage in visual processing are also modulated by perceptual load.

Active selection in situations of low perceptual load

There is compelling evidence that under conditions of low perceptual load, irrelevant items are perceived and identified (for review see Lavie & Tsal, 1994). This evidence converges from different methodologies, showing distractor perception from behavioural studies of concurrent interference (Lavie, 1995; Lavie & Cox, 1997; see Lavie & Tsal, 1994, for a review), NP (Lavie & Fox, 2000), and neural responses in sensory cortices (Rees et al, 1997). However, in low perceptual load situations normal young adults succeed in responding correctly, so somehow irrelevant information, although perceived and identified, is successfully prevented from being selected as the basis for a response. This implies the operation of an active selection process whereby the competition between relevant and irrelevant information for control of behaviour is resolved.

In principle, this active process could consist solely of extra activation applied to the relevant items, or it could also include active inhibition applied to the irrelevant items. Both these alternatives have been expressed in theories of selective attention. Some theories (e.g. Broadbent, 1970; Navon & Gopher, 1979; Van der Heijden, 1981) characterize distractor rejection purely in terms of excitatory mechanisms and their facilitatory effects on the processing of relevant information, while others postulate that irrelevant information is also actively rejected by means of inhibition (e.g. Neill, 1977; Tipper, 1985; Neill & Westberry, 1987; Houghton & Tipper, 1994). Evidence for the role of inhibition in selective attention has been based largely, to date, on the NP phenomenon. This evidence is reviewed in the following section.

Negative priming

The NP phenomenon provided a major impetus for interest in inhibitory mechanisms in selection, and remains the foremost line of behavioural evidence for that proposal. NP was first observed by Dalrymple-Alford & Budayr (1966), who found that naming the colour of a list of Stroop colour-words took longer when the relevant colour in any given item was always the one named by the ignored word in the previous list item. Neill (1977) generalised this finding to a discrete-trials procedure in which stimuli were presented in a random order and then afterwards analysed according to the relationship between the two trials (prime and probe) in each pair. These authors attributed the effect to suppression of the *response* to the irrelevant word, making it less readily available on the next trial. This paradigm was developed further by Tipper (1985, Tipper & Cranston, 1985), who also coined the term "negative priming", and used the phenomenon as the basis for a view of selective attention that includes inhibitory mechanisms. This view holds that irrelevant information is actively inhibited during selection, in complement to excitatory mechanisms acting on relevant stimuli, in order that responses can be based on relevant, rather than irrelevant stimuli.

NP and distractor interference

A puzzling question for the original distractor inhibition account of NP is that if NP reflects inhibition of distractors during selection, should there not be a simple relationship between NP and interference? Inhibition can be conceived of as an anticipatory process, such that it acts to prevent interference, or reactive, such that it acts to prevent strongly interfering distractors from determining responses. An anticipatory view predicts a negative relationship between NP and distractor interference, while a reactive view predicts a positive relationship. If the relationship between these two measures cannot be characterised as either reactive or anticipatory, then this presents a state of affairs too complex to be accounted for by a simple distractor inhibition account of NP such as that offered by Tipper & Cranston (1985). Indeed, the relationship between NP and interference has been the focus of much scrutiny in the debate as to whether inhibition is implicated in NP, and attempts to extract a simple conclusion from this issue have been frustrated by the complicated nature of the relationship between these two measures.

Positive relationships, in which increases in interference are accompanied by increases in NP, have been observed in numerous studies. For example, Fox (1994) found that concurrent interference and NP both increased as target-distractor separation was reduced in a letter identification task, and Ruthruff & Miller (1995) found that keeping target position constant eliminates interference and NP, also in a letter identification task. Moore (1996) found that concurrent interference and subsequent NP were both abolished in a letter identification task in which the distractor letter was presented later than the target, compared to when they onset at the same time. Tipper, Lortie & Baylis (1992) used a task in which subjects reached to press an illuminated button in a 3D stimulus board while ignoring another illuminated button of a different colour, and found that NP and interference both increased when the prime target position was closer to the hand compared to when it was further away. These studies suggest that numerous factors that affect concurrent interference also affect subsequent NP in the same way.

Evidence for a negative relationship between NP and interference, in which the two measures co-vary inversely, has also been produced in the literature. For example, Allport, Tipper & Chmiel, (1985) found no interference, but significant NP, when target location was predictable, and significant interference, but unreliable NP, when target location was unpredictable. Also, Richards (1999) found that pre-cueing the position of the prime target reduced concurrent interference yet increased subsequent NP in a word identification task. The main suggestion of negative relationships comes from individual differences studies, which have demonstrated that compared to young normal adults, NP is diminished, while interference is increased, in children (Tipper, Borque, Anderson & Brehaut, 1989), the elderly (Hasher, Stolzfus, Zacks & Rympa, 1991; Tipper, 1991), and subjects high in schizotypy (Beech & Claridge, 1987).

Completing the set of possible relationships between NP and interference, observations of apparent independence between the two measures are numerous. For example, Klein & Christie (1995) observed that increasing the similarity between target and distractor (e.g. using similar-shaped letters such as "C" and "G" rather than less similar letters such as "C" and "E") increases interference but does not affect NP, while Beech, Agar, & Baylis, (1989) found NP to be modulated by stimulus type (colour-words vs. pseudocolour words, e.g. "Ref", "Groit", and "Blor") while interference was not. Driver & Tipper (1989) found that in a Stroop-like task in which items of a certain colour were to be counted, interference was observed when the target items have an incongruent identity (i.e. when they are digits incongruent with the correct answer), but not when the non-target items did (as in Francolini & Egeth, 1980). NP, however, was equivalent in both these conditions, and thus did not vary as a function of interference in the prime. In a target localisation task, Tipper, Weaver, Kirkpatrick & Lewis (1991) observed that masking the task stimuli had no effect on the level of interference, but reduced the level of NP. Also, in contrast with the finding by Richards (1999), pre-cueing the position of the prime target has been found to decrease interference yet not affect NP in a letter identification task (Fox, 1994; 1995).

Clearly, NP and interference are not characterised by a simple linear relationship. The complexity of this relationship is not accounted for by the original distractor inhibition account of NP. While this in itself does not constitute evidence against the involvement of inhibition in selection, it does cast doubt on the ability of a simple distractor inhibition view to provide a comprehensive account of the NP phenomenon.

The episodic retrieval account

Another problem for a simple distractor inhibition account of NP is posed by alternative accounts of NP which attribute the phenomenon to processes of episodic retrieval in the probe, rather than distractor inhibition in the prime. An initial suggestion along these lines was made by Tipper, Weaver, Cameron, Brehaut & Bastedo (1991), who suggested that inhibition actually alters the stored representation of the ignored prime distractor, such that the inhibited state of that item is stored in its representation. On this account, NP is dependent on the prior experience of ignoring a stimulus in the same context being reinstated.

The episodic retrieval account was developed by Neill and colleagues (Neill & Valdes, 1992; Neill, Valdes, Terry & Gorfein, 1992), who suggested that NP results from retrieval in the probe trial of prior processing episodes involving the target stimulus. If the stimulus had previously been ignored, then the episodic trace would carry a "do not respond" tag which would conflict with the current requirement to respond to the stimulus and thereby slow reaction times. Neill et al.'s episodic retrieval account in fact proposes that NP is not dependent on distractor inhibition in the prime: instead, the slowing of probe-trial RTs is attributed to the retrieval in the probe trial of prior episodes involving that stimulus, and the ensuing conflict between the "do not respond" tag and the current requirement to respond to the stimulus.

On an episodic retrieval account, the level of NP should be affected by the discriminability of individual episodes from one another: if a prime episode is less discriminable from previous episodes, then its influence on performance should be reduced, resulting in less NP. A specific test of this discriminability account was conducted by Neill et al. (1992), who varied both the RSI between prime and probe displays within a trial and the RSI between the probe of one trial and the prime of the next (i.e. the RSI *before* the prime). The two RSIs in each prime-probe pair could be both short, both long, short then long, or long then short. Neill et al. found NP to be weakest on pairs with a short RSI before the prime and a long RSI between prime and probe (i.e. the condition which should allow the least discriminability of the prime episode), compared to all other combinations of RSI length. This result strongly implicates episodic retrieval processes, as retrieval of an episode is known to be strongly affected by the discriminability of that episode, whereas the process of distractor inhibition should not be affected by the discriminability of the prime display. However, it should be noted that subsequent studies by Hasher, Zacks, Stoltzfus, Kane & Connelly (1996) and Conway (1999) failed to replicate Neill et al. (1992)'s result.

Neill & Valdes (1992) predicted that if NP reflects the retrieval of a prior processing episode, then changes in the retrieval context may affect the likelihood of retrieval, and thus the probability of the occurrence of NP. In line with this prediction, a number of studies have suggested that the level of contextual similarity between the prime and probe trials is a determinant of the occurrence of NP. For example, in a letter identification task, Neill (1997) observed greater NP when the prime and probe displays had the same vs. different distractor-onset conditions, while in a similar task Fox & de Fockert (1998) observed greater NP when the prime and probe displays had the same vs. different contrast levels (see also Stolz & Neely, 2001). If the sole determinant of NP is distractor inhibition in the prime, then there should be no reason to predict that the similarity in context between prime and probe trials will have any effect on NP. Instead, the observed results implicate episodic retrieval mechanisms, as the similarity between episodes is a determinant of the probability of retrieval.

Although Wong (2000) has produced evidence that prime-probe similarity will not always modulate NP, as NP did not vary as a function of whether the position or presence of irrelevant parts of the display was the same for prime and probe trials, it has nonetheless been clearly demonstrated that similarity is one possible determinant of NP, and this is sufficient to present a serious challenge to the original inhibition account.

The feature mismatch account

Another alternative account of NP was offered in a study of NP for locations (Park & Kanwisher, 1994). In location NP tasks, subjects respond to the *location* of a pre-determined target item, while ignoring a distractor item in another location. NP in this task is observed in the form of slower responses when the target item in the probe occupies a location which had been occupied by a distractor item in the prime, suggesting that inhibition is applied to the location of the prime distractor (e.g. Tipper, Brehaut & Driver, 1990). In contrast to this, Park & Kanwisher (1994) required subjects to respond to the location of a target item in the prime and then the location of a *different target item* in the probe. For example, subjects might respond to the location of an "X" and ignore the location of an "O" in the prime, and then respond to the location of an "O" and ignore the location of an "X" in the probe. Thus, in this task, the same item could be a target in the prime, and a distractor in the probe, or vice versa.

While location NP is usually determined by whether the probe target occupies a location previously occupied by a distractor in the prime, in Park & Kanwisher (1994)'s task, NP appeared to be determined by whether the target location in the probe had been occupied by the same *item* in the prime. For example, if the probe target (e.g. "O") appeared in a location that had been occupied by a different item in the prime (e.g. "X"), then NP would occur. Thus, NP was found to occur when the probe target appeared in the same location as the prime target: a situation in which a distractor inhibition account predicts positive priming. Likewise, if the probe target (e.g. "O") appeared in a location that had been occupied by the same item in the prime (i.e. "O"), then *facilitation* would occur. Thus, facilitation was found to occur when the probe target appeared in the same location as the prime *distractor*: a situation in which a distractor inhibition account predicts *NP*.

These results cannot be explained by inhibition (or retrieval) accounts, as NP is clearly determined independently of the prior ignored/attended status of the probe location. Instead, Park & Kanwisher suggested that NP is determined by the presence of a mismatch in the binding of an item to a location: if in the probe you must respond to a location previously occupied by a different item, there is a mismatch between the previous binding and the current binding, resulting in NP.

However, while an inhibition account cannot explain these findings, it is also clear that the feature mismatch hypothesis cannot provide a general account for NP. In a target localisation task, Milliken, Tipper & Weaver (1994) observed NP when the prime distractor and probe target were identical in colour, identity and location (see also Tipper, Weaver & Milliken, 1995). Clearly, in such a case there is no feature mismatch, and so the feature mismatch account cannot explain all NP effects. Furthermore, other studies have observed NP when the level of mismatch is kept constant between ignored repetition and control trials (Fox, 1994; Neill, Lissner & Beck, 1990; Tipper, MacQueen & Brehaut, 1988). Nonetheless, while feature mismatch theory may not provide a comprehensive account of NP, it is clear that in at least some task situations the level of mismatch between features is one determinant of NP. This contributes to the difficulties in using NP alone as a means to investigate inhibition.

The temporal discrimination account

Recently, another alternative account of NP has been forwarded. Milliken, Joordens, Merikle & Seiffert (1998) suggested that the occurrence of NP depends on a process wherein the probe target item is categorised as "old" or "new". According to this temporal discrimination account, in attended repetition trials the probe target is easily categorised as "old", and the prior learned response can be quickly reinstated for maximum efficiency. In control trials, the probe target is easily categorised as "new", and responding can proceed algorithmically in line with the demands of the task. Crucially, in ignored repetition trials, the recently-ignored status of the probe target item entails that it is familiar enough to prevent it being easily categorised as "new", but not sufficiently familiar to allow retrieval of the correct response to that item. Thus, the delay on ignored repetition trials that constitutes the NP phenomenon is attributed to a delay in the process of categorising the probe target as "old" or "new". As such, the temporal discrimination account includes retrieval processes, but does not include reference to inhibition, or indeed any prime-trial processing.

The temporal discrimination account provides a cogent explanation for much of the available data on NP. For example, the findings implicating retrieval processes in NP, i.e. effects of context (e.g. Fox & De Fockert, 1998; Neill, 1997; Stolz & Neely, 2001) and long RSIs (e.g. Neill & Valdes, 1992, Tipper, Weaver, Cameron, Brehaut & Bastedo, 1991), are easily accommodated, as this account incorporates retrieval processes itself. Furthermore, the relationship between NP and distractor interference on the prime is not a challenge to this account, as it explicitly states that NP is dependent on the success of a process in the probe trial (the temporal discrimination process), and not on any processes in the prime trial. Also, Park & Kanwisher's (1994) findings on the effects of feature mismatches are accounted for by the idea that a featural match on one dimension (i.e. location) but not another (i.e. identity) will lead to conflicting tendencies to categorise a probe item as "old" and "new".

Milliken et al. (1998) focus on findings which suggest that NP is dependent on the occurrence of selection in the probe trial. Various researchers have observed that positive rather than negative priming occurs if the probe trial involves a single target with no accompanying distractor (e.g. Lowe, 1979; Milliken et al, 1998; Moore, 1994; Tipper & Cranston, 1985). According to the temporal discrimination hypothesis, subjects are less discriminative in categorising probe targets as "old" when there is no distractor present. When a distractor is present, on the other hand, more caution is employed, in order to avoid retrieving stored responses to the distractor rather than the target. This strategic difference entails a higher similarity criterion for a target to be categorised as "old", which results in longer RTs on ignored repetition trials where the categorisation process is more difficult.

Milliken et al (1998) also demonstrate that NP can be observed with only a single item, to which no response is required, in the prime trial. They claim that this situation constitutes the occurrence of NP without selection in the prime, which would constitute evidence against distractor inhibition accounts of NP. Similar findings have been produced by Milliken & Joordens (1996) and Neill & Kahan (1999). However, it is not necessarily the case that selection does not occur in this situation. There is much evidence that stimuli that are strongly associated with particular responses in a given context can automatically activate those responses even when they are not required (e.g. Coles, Gratton, Bashore, Eriksen & Donchin, 1985; Eimer, Hommel & Prinz, 1995; Lhermitte, 1983). Thus, in the context of a task in which responses are required for very similar stimuli (in the case of Milliken et al, 1998: the same items in a different colour), it is likely that the prime stimulus will evoke a response. As subjects are asked not to respond to prime stimuli, this response must then be suppressed. Nonetheless, although the finding of NP in the absence of overt selection in the prime can be accounted for in terms of inhibition, the temporal discrimination account still provides a significant challenge to inhibition accounts of NP, as it is able to accommodate many previous NP findings without making any reference to inhibition.

A more sophisticated inhibition model of NP: the Houghton & Tipper model

Although a simple distractor inhibition account cannot explain the effects of contextual similarity, or the relationship between NP and distractor interference, a more sophisticated model forwarded by Houghton & Tipper (1994; 1998; Houghton, Tipper, Weaver & Shore, 1996) can accommodate many seemingly awkward findings. For example, the model can account for the relationship between NP and interference in the prime trial. The model adopts a reactive inhibition view of NP, proposing that inhibition reacts against response competition from distractors, such that a more strongly competing distractor engenders stronger inhibition. However, the model proposes that what is reacted to is not the observable concurrent interference itself, as this interference may not accurately reflect the degree of activation of an individual distractor. In particular, interference may be affected by variables which do not necessarily affect NP in the same way. For example, inhibition is predicted to require time to build up after stimulus onset, so reducing the interval between prime and probe should reduce NP without affecting interference. In a localisation task, Houghton, et al. (1996) found exactly this result: reducing the interval between prime and probe abolished NP without changing the level of interference.

Another prediction is that inhibition is distributed among the distractors, such that any one distractor is less inhibited than it would be if it were the sole distractor. Thus, increasing the number of distractors should lead to increased interference, but reduced NP. Again, this prediction was borne out by Houghton et al. (1996)'s results. Finally, increasing the activation strength of a distractor should lead to increases in both NP and interference. Houghton et al. (1996) found that increasing distractor salience (via contrast) increased both NP and interference, in line with the prediction that more inhibition is required for salient stimuli. Thus, the three relationships between NP and interference observed in the literature – positive, negative and no relationship – were all produced in Houghton et al (1996)'s study, in accordance with the predictions of the Houghton & Tipper model.

Another aspect of NP that is accounted for by the Houghton & Tipper model is the characteristics of the effect when short prime-probe SOAs are used. Studies with a short SOA between the prime and probe stimuli have provided evidence that NP requires some time to develop. For example, Lowe (1985) observed no NP at 50 ms

SOA between prime and probe, and significant NP from 100 ms SOA upwards. Also, Neill & Westberry (1987) and Yee (1991) found NP to increase over the first few hundred milliseconds of SOA. Similarly, studies in which speed is emphasised over accuracy have tended to find no NP (Neill, 1979; Neill & Westberry, 1987) or facilitation of responses to distractors presented as subsequent targets (Neill, 1977; Neumann & DeSchepper, 1992). These results suggest that initially after the prime presentation distractor activations are high, only becoming suppressed after a short delay.

Intuitively, this pattern may suggest that any inhibition involved in producing NP occurs *after* selection of targets over distractors, for were the inhibition to occur *during* target selection then one would expect its effects to be observable straight away. However, Houghton & Tipper (1994) suggested that inhibition acts as a counterforce to the activation of the distractor representation, which is triggered by the distractor stimulus. Thus, while the distractor is present, inhibition simply counteracts the distractor activation, keeping its overall activation level roughly at baseline. On this model, it is only on offset of the distractor stimulus that the item's activation drops below baseline (the so-called *inhibitory rebound*), as the inhibition is no longer countered by the stimulus-driven activation. Thus, the model predicts that the distractor representation will be active at short SOAs, and suppressed at longer SOAs, in line with the empirical findings.

It should also be noted that the small size of the inhibitory rebound allows the Houghton & Tipper model to account for Milliken et al. (1998)'s findings that NP is dependent on selection in the probe. If selection is required in the probe, the response competition between target and distractor entails that any factor that reduces the target activation, such as the inhibitory rebound from selection in the prime, will make a difference to the speed of target selection in the probe (resulting in NP). However, if there is no requirement for selection in the probe, then the small difference in target activation caused by the inhibitory rebound makes no difference to the ease with which the target is selected, as there is no distractor to compete with it (thus resulting in no NP).

Houghton & Tipper's model also incorporates processes of episodic retrieval, along the lines indicated by Tipper, Weaver, Cameron, Brehaut & Bastedo (1991). On their model, the process of inhibition on the prime trial alters the stored representation of the ignored stimulus, such that its status on retrieval in the probe is different to what it would be had it not been recently ignored. Such a hybrid model is akin to a retrieval account of NP, with the significant exception that the means of selection is considerably more thoroughly specified. "Pure" retrieval accounts do not really attempt to elucidate the means of selection in the prime, other than proposing the assignment of "do not respond" tags (e.g. Neill & Valdes, 1992; Neill, Valdes, Terry & Gorfein, 1992), thus the Houghton & Tipper hybrid model has a clear advantage in this respect. Note also that such a model easily accounts for the observation that NP can be modulated by variables likely to affect inhibition (e.g. age) and retrieval (e.g. stimulus degradation) separately in the same experiment (Kane, May, Hasher, Rahhal & Stolzfus, 1997). Thus, while strong inhibition accounts attributing NP to the persistence of an active process of inhibition between prime and probe trials cannot account for many of the observed characteristics of NP, the Houghton & Tipper (1994, 1996) model shows that a more sophisticated model is capable of explaining a large proportion of the data in terms of processes of inhibition as well as memory retrieval.

In conclusion, there seems to be evidence that NP reflects both distractor inhibition processes and memory retrieval processes. It is therefore important to examine the hypothesis that active rejection of perceived distractors in situations of late selection (e.g. low perceptual load) involves inhibition of response tendencies by another means that is not subject to alternative accounts in terms of episodic retrieval.

Different levels of cognitive inhibition

In seeking an alternative line of behavioural evidence for the role of inhibition in selective attention, we designed a new paradigm in which we engage inhibition in one task and then gauge the effects on selective attention performance in a subsequent task. Our theory proposes that in low perceptual load situations, distractors are perceived, and these distractors activate response tendencies which compete with the desired response. Thus, active inhibition of these unwanted response tendencies is required. There have been demonstrations that response tendencies are activated by distractors in selective attention tasks. For example, in a flanker task requiring manual responses, Coles, Gratton, Bashore, Eriksen & Donchin (1985) observed activation of responses to distractors via the electromyographic (EMG) responses of flexor muscles used in hand movements (see also Eriksen, Coles, Morris, & O'Hara, 1985). Thus, as our theory proposes that selective attention uses inhibition to prevent response tendencies to irrelevant yet perceived distractors, we only considered tasks that could potentially engage inhibition of response tendencies[1].

In this section I discuss the types of inhibition involved in the dominant inhibition paradigms in the attention literature, focusing on whether these paradigms are likely to engage response inhibition, and thus are likely to have a direct effect on inhibition of responses to distractors in a subsequent flanker task.

Inhibition of return

The phenomenon of inhibition of return (IOR) is typically observed in an orienting paradigm, in which one of two locations either side of fixation is cued, and subsequently a response must be made (e.g. a target localisation response) to a target item which appears at one of the locations. Posner & Cohen (1984) observed that when the target appeared in the cued location within 300 ms of the cue, responses were facilitated relative to responses to targets on the uncued side, indicating that attention had been allocated to the cued location. However, when the target appeared more than 300 ms later than the cue, responses were *slowed* to targets in the cued location vs. the uncued location. This slowing effect was interpreted as indicating that attention was inhibited from easily returning to the cued location.

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[1] Cognitive studies of inhibition have addressed inhibition at various levels, such as semantic processing (e.g. Neely, 1977; Gernsbacher & Faust, 1991), directed forgetting (e.g. Bjork, 1989; Hasher & Zacks 1995), or sensory inhibition phenomena such as habituation (e.g. Solokov, 1963; Cowan, 1988). These levels of processing are unlikely to involve response inhibition, and are thus unlikely to have a direct effect on the inhibition of responses to distractors in a selective attention task. My review thus excluded such tasks, as they are clearly not related to inhibition of responses.

Further studies on IOR have suggested that the effect reflects inhibition of representations of locations or of objects. Evidence for IOR being applied to objects rather than locations comes from studies in which the task stimuli are moved between cue presentation and target presentation. For example, Tipper, Driver & Weaver (1991) cued one of two boxes either side of fixation, moved the boxes to new positions, and then presented a target in one of the boxes. They found that IOR moved with the boxes, such that responses to targets in the cued box were slowed even when the box was no longer in the cued location. However, while this study suggests an object basis for IOR, a later study using a similar method showed that when an uncued object is moved to the cued location, responses are slowed to targets in that object, suggesting that a component of IOR remains at the cued location (Tipper, Weaver, Jerraut & Burak, 1994). Subsequent studies have debated the extent to which these two components of IOR are separable (e.g. Jordan & Tipper, 1998; Müller & von Mühlenen, 1996; Weaver, Lupiàñez & Watson, 1998).

Importantly, the fact that IOR seems to attach itself to objects or locations clearly suggests that the inhibition involved is at a level other than the active inhibition of responses. Whether the IOR in any particular situation involves objects or locations, the nature of the inhibition involved seems clearly distinct from active response inhibition. Specifically, it is not the case that responses to the cued objects/locations are prepared, and then suppressed by an inhibitory mechanism reacting to the activation of those responses. Rather, IOR seems to reflect a bias against re-allocating attention to the cued object/location (e.g. Handy, Jha & Mangun, 1999; Posner & Cohen, 1984; Reuter-Lorenz, Jha & Rosenquist, 1996) or a bias against preparing a response to the cued object/location (e.g. Klein & Taylor, 1994; Taylor

& Klein, 1998). In other words, the inhibition in IOR seems to act as a bias against the processes leading to response generation, rather than acting as an inhibitory reaction to an already-generated response. Therefore, as IOR does not seem to involve active inhibition of prepared responses, it is unlikely to have an effect on the extent to which response tendencies toward a distractor are inhibited in a following task.

One possible alternative account of IOR which does involve active response inhibition is the idea that because no response is required to the cue, there may in fact be some inhibition of potential responses toward the cue, the after-effects of which might lead to a reduced ability to respond to further targets at that location. However, this account is ruled out by the findings that IOR occurs even in a continuous target-target paradigm, in which each stimulus requires a response. In such a paradigm, IOR is observed when the target appears in the same position as the previous target (Maylor & Hockey, 1985; Posner & Cohen, 1984). Thus, as IOR occurs even when there is unlikely to be any need to avoid responses to the cue (as the cue itself is a target), this rules out any account attributing IOR to the need to prevent responses to the cue.

Thus, rather than inhibition being applied to individual responses, the inhibition in IOR is applied to locations or objects in a representational map. As such, it is the inhibition of these representations which impairs the generation of responses to items presented there, rather than inhibition applied directly to responses. An IOR paradigm cannot therefore be assumed to provide a means of manipulating response inhibition.

Visual Marking

The visual marking paradigm involves a search for a target that is defined by a conjunction of two features among distractors which may share one of those features. In such tasks, search is typically serial, such that every item is searched until the target is found, in contrast with tasks involving search for an item defined by a single feature, in which targets typically "pop out" (Treisman & Gelade, 1980). The visual marking effect is observed when a subset of the distractors is first presented alone, and then the target and the remaining distractors are added to the display. In such a preview condition, search for the target is as efficient as if the previewed distractors were not present at all. That is to say that the slope of the search function (i.e. the time taken to find the target expressed as a function of the number of items in the display) indicates that subjects were able to exclude the previewed items from the process of serially searching each item (Watson & Humphreys, 1997).

This visual marking effect seems to reflect inhibition of either individual objects or individual locations when the stimuli are static, and to reflect inhibition of entire features (in all objects) when the stimuli are moving. The basic finding of visual marking of static stimuli does not inform us as to whether it involves inhibition at the level of locations or at the level of objects. It is clear that the old objects are not searched, but it is possible that the inhibition is applied to the object's location, rather than to the entire representation of the object.

There is a suggestion that visual marking involves the inhibition of objects, rather than locations, in that a preview benefit does not occur for a place marker (e.g. a box) that is presented in the preview display, and then replaced by a non-target at the same location when the rest of the display is presented. Similarly, if an incomplete non-target item (e.g. half a letter) is presented in the preview display, and then completed when the rest of the display is presented, there will be no preview benefit for that location (Watson & Humphreys, 1997). If visual marking operated at the level of locations, then arguably searching a particular location during the preview period should result in a preview benefit for that location regardless of the item occupying that location. However, other experiments have shown that a dynamic change at a location or within an object (e.g. offsetting and re-onsetting) is sufficient to prevent a preview benefit at that location or object (Watson & Humphreys, 1997). Thus, the change in the stimulus in the previous experiments (e.g. the change from a half letter to a complete letter) could be responsible for the lack of a preview benefit.

Furthermore, Watson & Humphreys (2000) demonstrated that detection of a probe dot was impaired when the dot appeared in the location of a previewed distractor, relative to when the dot appeared in a location that was not previewed. Although the previewed object remained present when the probe dot was presented, the fact that the dot did not form part of the previewed object, but merely occupied some of the space delineated by the object (e.g. it appeared underneath the bar of a letter "A"), suggests that detection of the dot suffered because inhibition was applied to the location, rather than the representation of the object. This evidence is only suggestive, however, and thus while Watson & Humphreys (1997) propose that visual marking operates at the level of locations, the available evidence does not strongly differentiate between a location-based and an object-based account of visual marking of static stimuli. However, as with IOR, visual marking may involve location-based or object-based inhibition, but neither alternative seems to involve the idea that marking is due to the inhibition of responses.

In contrast to static displays, visual marking in moving displays appears to operate at the level of inhibiting a feature (e.g. a particular colour) in all objects. In static displays, when a subset of the distractors of one colour are previewed, and more distractors of the same colour are later added along with the target, the previewed items are selectively inhibited, and the new distractors of the same colour are not inhibited (Theeuwes, Kramer & Atchley, 1998; Watson & Humphreys, 1997). However, in moving displays, the evidence for inhibition at the level of features across all objects is that the search slopes indicate that preview of some distractors leads to all distractors of the same colour being excluded from search. That is, new distractors of the same colour as those previewed, that are not themselves previewed, do not increase search RTs. This suggests that inhibition has been applied at the level of that particular colour, with the result that all items of that colour are uniformly excluded from search. Thus, all the items of the same colour are either inhibited together or not inhibited together in moving displays (Olivers, Watson & Humphreys, 1999; Watson & Humphreys, 1998; Watson, 2001).

While visual marking seems to be an active process in that it is diminished when resources are engaged in a concurrent digit naming task (Watson & Humphreys, 1997), the above evidence suggests that the inhibition involved is at the level of individual objects or locations (with static stimuli) or features across all objects (with moving stimuli), and serves to prevent the inhibited items being candidates for visual search, rather than to suppress responses to those items. As such, visual marking does not involve response inhibition, and is therefore unlikely to lead to carry over effects on the efficiency of inhibition of responses to distractors in a following task.

Antisaccade tasks

In an antisaccade task, the subject fixates a central point, and must execute a saccade *away* from a peripherally presented stimulus (Hallett, 1978; Hallett & Adams, 1980), a process which does seem to require active response inhibition. Performance of the antisaccade task involves an active, controlled process, as evidenced by poorer antisaccade task performance when subjects are engaged in an attention-demanding arithmetic task (Roberts, Hager & Heron, 1994), when subjects are engaged in the Random time Interval Generation task (Stuyven, Van der Goten, Vandierendonck, Claeys & Crevits, 2000), or in individuals with a lower working memory span (Kane, Bleckley, Conway & Engle, 2001). The prepotency of the reflexive prosaccade response is strong, as demonstrated by the high rate of erroneous prosaccades (30-80%) while subjects learn the task (Hallett, 1978). Thus, active response inhibition is required to overcome this prepotent tendency and to allow an endogenous saccade to be carried out in its place. However, while the antisaccade task does seem to involve active response inhibition, it involves inhibition of an oculomotor response rather than of a manual response. It is not clear whether manipulating inhibition of oculomotor responses would have any effect on inhibition in a task involving manual responses such as the flanker task employed in this thesis. While investigations of our predictions across response modalities may serve as a direction for future research, for the purposes of establishing the predicted effect in this thesis, we wish to restrict our investigations to manipulations of inhibition of manual responses.

Tasks involving inhibition of manual responses

Three tasks involving inhibition of manual responses were used in the experiments in this thesis. As each of these tasks is discussed in detail in the chapter in which it appears, this chapter contains only a description of the three tasks, and a brief indication of the evidence suggesting that each involves the active inhibition of a dominant response.

Stop signal tasks

The active inhibition of responses has been most directly investigated in the stop signal paradigm (Lappin & Eriksen, 1966; Logan, 1981). In the stop-signal paradigm, subjects perform an RT task, and on some trials a stop signal follows the target stimulus, indicating that the subject must stop their response. The typical stop signal paradigm involves a visual choice reaction time (CRT) task (e.g. discriminate As and Bs from Cs and Ds) and an auditory tone presented on some trials as a stop signal (e.g. Logan & Cowan, 1984). Visual stop signals (e.g. Logan & Irwin, 2000), and simple reaction time tasks (e.g. Lappin & Eriksen, 1966; Ollman, 1973; Logan, Cowan & Davis, 1984) have also been successfully used in the stop signal paradigm. In the task, the subject is instructed to respond as quickly as possible to the task stimulus, but also to stop this response upon encountering a stop signal.

Thus, the task seems to involve a voluntary act of active response inhibition in order for correct performance to be achieved.

This suggestion is borne out by evidence that the effects of varying temporal factors, such the interval between the target and the stop signal, are in line with a race model in which response preparation occurs in parallel with processes of response inhibition (e.g. Logan & Cowan, 1984). Such data demonstrate that if the stop signal is not presented sufficiently early, responses will be executed despite the presentation of the stop signal. This is a clear indication that inhibition in stop signal tasks acts against responses that are being actively prepared.

Also, there is evidence that response activation occurs in the muscles of the hand and arm (measured via EMG; e.g. Jennings, Van der Molen, Brock, & Somsen, 1992), and sometimes even in partial movements (measured via a dynamometer; e.g. De Jong, Coles, & Logan, 1995) on some trials in which a signal is presented and the response successfully stopped. Again, this indicates that the stop signal paradigm involves active inhibition of prepared, and sometimes even initiated responses. Thus, engaging such response inhibition in a stop signal task should affect the availability of inhibition for the suppression of responses to distractors in a flanker task.

Spatial S-R mapping tasks

There is an extensive literature on tasks which require subjects to respond in a manner that does not correspond to spatial aspects of the task stimuli. For example, in a task where subjects respond to a left or right pointing arrow with two keys positioned to the left and right of each other, the task might require a left-key response to a right-pointing stimulus, and a right-key response to a left-pointing stimulus. In this example, in which the stimulus-response (S-R) mapping is spatially incongruent, the typical finding would be that responses are slower than when the S-R mapping is spatially congruent (i.e. a right-key response to a right-pointing stimulus, and vice versa; e.g. Fitts & Seeger, 1953). The literature suggests that in such tasks, the spatially congruent response is automatically activated, with the result that if the task itself requires a spatially incongruent response, the congruent response must be suppressed.

Evidence for the automatic activation of spatially congruent responses is provided by studies showing that responses which do not correspond to spatial properties of the stimulus are slower than those that do correspond, even when these spatial properties (e.g. target location) are *irrelevant* to the task itself (e.g. Simon, 1990). Also, numerous electrophysiological studies have demonstrated that activation of spatially congruent responses occurs on trials where these responses are incorrect (i.e. trials with an incongruent S-R mapping). For example, activation of spatially corresponding but incorrect responses has been shown at the cortical level (measured via ERPs; e.g. De Jong, Liang & Lauber, 1994), and at the level of muscle activation (measured via EMGs; e.g. Hasbroucq, Burle, Akamatsu, Vidal & Possamaï, 2001). Also, neural recordings in monkeys have demonstrated that when a spatially incongruent response is required, the spatially corresponding response is activated before the correct response is activated (e.g. Georgopoulos, Lurito, Schwartz & Massey, 1989). In sum, there is a substantial body of evidence to suggest that spatially congruent responses are dominant over spatially incongruent responses, and that when the incongruent response is required, the congruent response is nonetheless automatically activated, and thus requires inhibition. This led us to expect that engaging inhibition via the demand to make spatially incongruent responses should reduce the availability of inhibition for suppressing responses to distractors in a subsequent task.

Stroop colour-word tasks

The Stroop colour-word task (Stroop, 1935) is another task in which the execution of an incongruent response involves the suppression of a dominant congruent response. In the Stroop task, subjects are asked to name the colour of a word while ignoring the word's identity. The word can be either congruent with its colour (e.g. "BLUE" printed in blue), incongruent with its colour (e.g. "RED" printed in blue), or neutral (e.g. the word "CHAIR" or the letter string "XXXX" printed in blue). Substantial congruency effects are found in the Stroop colour word task: RTs are slower when the word is incongruent with its colour than when it is congruent or neutral. The dominance of the response to the word over the response to the colour is evident in the fact that when subjects are required to read the word and ignore the colour, very little, if any, interference from incongruent colours is observed on word-reading RTs (e.g. Duncan-Johnson & Kopell, 1980; 1981; Stroop, 1935). While this dominance of responses to words over responses to colours is strongest in tasks using vocal naming and reading responses (e.g. Logan Zbrodoff & Williamson, 1984), it is nonetheless robust in tasks using manual responses to the colours or words (e.g. Pritchatt, 1968; Sugg & McDonald, 1994). As with spatial S-R mapping tasks, the strength of activation of the dominant response (to the word) creates a need for active inhibition of this response when a response to the colour that is incongruent with the word is required by the task.

Evidence for a central locus of response inhibition

The idea that inhibition in one task will have carry-over effects on distractor rejection in a subsequent selective attention task, even if the two tasks involve different stimuli, different responses and different response effectors (i.e. different hands), requires that response inhibition does not just involve peripheral effects at a purely motoric level (as carry-over effects from this would be confined to repeated responses in the same task with the same effector, etc.).

Previous studies suggest that response inhibition may indeed involve relatively central processes. In one study, Tipper, MacQueen & Brehaut (1988) found that the strength of NP was not affected by variations in response modality (vocal or manual), or by whether the response modality was the same in the prime and probe. This suggests that, to the extent to which NP indicates distractor inhibition, this inhibition is more central than any of these particular response modalities.

Another line of evidence has come from neurophysiological studies of the stop signal paradigm and other go/no-go tasks (that are similar to the stop signal paradigm except that, rather than a stop signal, these tasks assign a go response to some stimuli and a no-go response to other stimuli. ERP studies of both stop signal and go/no-go tasks have found that stopping a response is associated with an N200 potential that exerts its maximum over the frontal cortex, and is thought to reflect a central inhibition mechanism (e.g. Van Boxtel, Van der Molen, Jennings & Brunia, 2001). The amplitude of this wave is greater for no-go than for go stimuli (e.g. Kok, 1986), and it becomes greater when the extent of motor preparation for the response that is stopped is increased, thus making response inhibition more difficult (e.g. Jodo & Kayama, 1992; Eimer, 1993). Van Boxtel et al. (2001) also found that the amplitude of the N200 was related to the efficiency of inhibition, as subjects with faster estimated reaction times to the stop signal also exhibited a greater N200.

Sasaki, Gemba & Tsujimoto (1989) recorded from depth electrodes in non-human primates, and found a set of cells in the equivalent of Brodman's area 46 in the human frontal cortex that fired in response to a no-go stimulus in a go/no-go paradigm. Excitation of these cells during a standard response task (i.e. not go/no-go) resulted in an attenuation of activity in the premotor cortex and subsequently a suppression of responses.

As well as the considerable evidence for response inhibition being associated with a mechanism in the frontal cortex, some researchers have suggested that this central mechanism is supplemented by another mechanism that is downstream from the motor cortex (De Jong, Coles, Logan & Gratton, 1990; De Jong et al., 1995). De Jong et al. (1990, 1995) suggest that this mechanism serves to shut off a process which amplifies and sustains a motor command until completion. However, it is unlikely that such a mechanism would be located at a point specific to an individual hand. Hoshiyama, Kagiki, Koyama, Takeshima, Watanabe & Shimojo (1997) found that in addition to the attenuation of agonist muscle activity in the hand (as indexed by EMG) after a response has been stopped, antagonist muscle activity is also attenuated, suggesting that antagonist muscles could not be a source of peripheral inhibition. Also, it has been shown that the excitability of the spinal cord is no lower on stop trials than on go trials, suggesting that inhibition is not exerted at the spinal cord level (Hammond & Choo 1994; Van Boxtel, Jacobs, Van der Molen, Jennings & Brunia, 1996). Thus it is likely that such a mechanism, if it exists, is located upstream from the spinal cord.

Neuropsychological evidence for the reliance of response inhibition on intact frontal-lobe functions

Studies of neuropsychological patients with frontal lesions has provided another line of evidence that successful inhibition of unwanted responses involves central cognitive processes, and that response inhibition does not simply rely on a peripheral mechanism at the motoric level, as it depends on intact frontal function.

The phenomenon of perseveration in frontal patients seems to reflect a failure to inhibit responses that have been associated with certain stimuli on previous occasions. Perseveration refers to behaviours in which, after a response is given to a task, this response will be given again on subsequent trials even if this response is no longer appropriate. For example, in the Wisconsin Card Sorting Test, subjects sort cards according to shape, colour or number, and are alerted after each mistake. When the experimenter changes the category to sort by, frontal subjects persist with the original category, despite feedback that enables normal subjects to realise what has happened and begin sorting by a different category (e.g. Milner, 1964). This perseverative behaviour suggests that the frontal patient cannot easily inhibit the inappropriate response which has become associated with the task stimuli on previous trials. Similar results come from the delayed response task, in which the subject watches an object being hidden, and then after a delay he or she must attempt to retrieve it. Although they have seen where the object was placed, frontal patients tend to search the location where the object was found on the previous trial, suggesting that they cannot inhibit this previously-made response (e.g. Milner, 1964; Schacter, Moscovitch, Tulving, McLachlan & Frendman, 1986).

Patients with frontal-lobe damage also exhibit behaviour that suggests an inability to inhibit responses to cues in the environment. An example is the phenomenon of ‘utilization behaviour’, in which patients compulsively reach for, grasp and use familiar objects whether or not the situation calls for it (e.g. Lhermitte, 1983; Shallice, Burgess, Schon & Baxter, 1989; Brazzelli & Spinnler, 1998). When explicitly asked not to respond to certain stimuli, frontal patients show a greater level of responses to these stimuli than do normals. For example, Godefroy & Rousseaux (1996) instructed frontal patients to press a key in response to stimuli presented visually, but not to stimuli presented auditorily. The patients exhibited a higher rate of erroneous responses to the irrelevant auditory stimuli than normal control subjects, demonstrating a failure to inhibit unwanted responses.

Another failure to inhibit responses was reported by Paus, Kalina, Patockova, Angerova, Cerny, Mecir, Bauer & Krabec (1991), who instructed frontal patients to keep their gaze fixated centrally, thus requiring the suppression of reflexive saccades triggered by the sudden appearance of novel, peripheral visual stimuli. The patients were less able than normal controls to inhibit these reflexive saccades. Similarly, in anti-saccade tasks, in which subjects must execute a saccade *away from* a stimulus, frontal patients show many more erroneous reflexive saccades toward the stimulus (Guitton, Buchtel & Douglas, 1985), again suggesting that they cannot easily inhibit prepotent responses.

As well as in their overt behaviour, frontal patients also exhibit a deficiency in inhibition at the electrophysiological level. For example, Knight, Hillyard, Woods & Neville (1981) recorded ERPs from the scalps of patients with a unilateral frontal lesion. While in the normal population, *attended* stimuli elicit an ERP with enhanced negative components compared to unattended stimuli (Hillyard, Hink, Schwent & Picton, 1973), Knight et al (1981) found that frontal patients showed an enhanced negativity related to *unattended* tones when they were presented to the contralesional ear. This finding suggests a deficit in inhibition of the distracting tones by the frontal region contralateral to the tone.

Chao & Knight (1998, also Chao and Knight, 1995) presented patients with focal dorsolateral prefrontal lesions with an auditory cue and a subsequent target sound, and requested that they indicate whether or not these two sounds were identical. On some trials a silent interval separated the cue and the target, while on others a series of irrelevant short tones filled the interval, acting as distractors. The behavioural data showed that the patients were more susceptible to the distractors, committing more errors in the distractor condition than the normal controls. The electrophysiological data showed that the frontal patients also generated enhanced evoked responses (in the primary auditory cortex) to the distractor tones compared to normal controls.

Overall, the evidence from frontal patients shows that they are unable to effectively inhibit irrelevant responses, such as those given on previous occasions that are no longer appropriate, and responses that are afforded by stimuli that they have been instructed not to respond to. This excess of response production is consistent across overt responses and electrophysiological responses. Also, it is useful to note that elderly subjects, who suffer a greater proportion of age-related cell loss in the frontal lobes than in the rest of the cortex (Creasey & Rapoport, 1985; Huttenlocher, 1979), exhibit similar deficits to the frontal patients. For example, elderly subjects show an increased tendency to respond to irrelevant stimuli both overtly (Dywan & Murphy, 1996), and in terms of ERPs (Chao & Knight, 1997) and skin conductance orienting responses (McDowd & Filion, 1992). All these lines of evidence converge on the suggestion that the successful inhibition of unwanted responses is dependent on a cortical mechanism in the frontal lobes rather than a peripheral mechanism.

In summary, the evidence suggests that the mechanisms responsible for response inhibition are located at a point in the response process that is relatively central and not specific to individual effectors. Moreover, the bulk of the evidence implicates the frontal cortex as the locus of response inhibition: frontal patients cannot stop themselves from making unwanted responses, and the process of stopping unwanted responses is associated electrophysiologically with the frontal lobes. The evidence reviewed is encouraging for our prediction that response inhibition in one task will have carry-over effects on distractor rejection in a subsequent selective attention task, even when both tasks employ different stimuli and require different responses, with the use of different effectors (e.g. the left and right hands) in each task.

Inhibition as a limited capacity mechanism

The hypothesis of the present research that engaging inhibition in one task will lead to inhibition being less available for distractor rejection in the flanker task is based on the premise that response inhibition has limited capacity. Numerous studies have provided evidence in support of this claim by showing that lower availability of controlled attentional resources, either through task load or individual differences in attentional capacity, leads to reduced efficiency in inhibitory tasks.

In the NP paradigm, Neumann & DeSchepper (1992) found that NP decreases as the number of irrelevant distractors increases. This finding is equivalent to the fan effect in memory tasks: the more facts studied about a concept in the learning phase, the longer it takes to retrieve any single fact, suggesting that a limited resource was distributed among the related facts (e.g. Anderson, 1976; King & Anderson, 1976). In Neumann & DeSchepper's task, the results suggest that a limited pool of inhibitory resources is applied to the distractors, such that if the number of distractors increases, less inhibition is applied to each one. A less-strongly inhibited distractor would then produce less NP when it appears as a target.

Houghton, Tipper, Weaver, & Shore (1996) found similar results to Neumann and colleagues, in that NP was found to decrease as the number of prime-trial distractors was increased from 1 to 2. However, Houghton et al. questioned Neumann & DeSchepper (1992)'s interpretation of the inhibitory fan effect. Houghton et al. suggested that this result was explicable solely in terms of each distractor receiving less activation, and thus requiring less inhibition as a result.

Thus, in their view, a limited capacity inhibition mechanism is an unnecessary assumption, as the results could reflect an inhibition mechanism with *unlimited* capacity which is simply reacting to smaller levels of activation. While it is true that the fan effect in NP is not necessarily indicative of a limited capacity inhibition mechanism, the findings of Neumann and colleagues are certainly *consistent* with the idea of limited capacity inhibition. Furthermore, there are other lines of evidence which support this notion.

Engle, Conway, Tuholski & Shisler (1995) interpolated to-be-remembered words between trials in a NP paradigm. At the end of a sequence of five trials, the words were to be recalled. Engle et al. observed that as the working memory (WM) load increased from the first to the fifth trial, lower levels of NP were observed in the selection task. These results suggest that the engagement of controlled attentional resources (e.g. WM load) limits the operation of inhibitory functions. Consistent with this suggestion is the finding that individuals with a lower WM capacity produce smaller NP effects (Conway, Tuholski, Shisler & Engle, 1999). However, reduced WM capacity, or increased WM load, would be just as likely to affect memory retrieval of prime episodes in the probe as it would be to affect distractor inhibition in the prime. Thus, findings of WM capacity or load affecting NP can also be explained in terms of a memory retrieval component of NP.

However, effects of WM load and capacity on inhibition tasks which do not involve episodic retrieval provide converging evidence for the suggestion that inhibition is a limited capacity mechanism. Findings of impaired inhibition with WM load have also been produced in the antisaccade task (Roberts, Hager & Heron, 1994), as well as impaired inhibition in individuals with low WM capacity in both the antisaccade (Kane, Bleckley, Conway & Engle, 2001) and Stroop (Kane & Engle, 2002) tasks. Also, Rosen & Engle (1998) found that individuals with low WM capacity showed less of an effect of inhibition of previously-suppressed associates in a paired associates task. Clearly, the findings from numerous inhibition tasks are consistent with the idea that the operation of inhibition is dependent on limited resources which are depleted when WM load is high, or when an individual has low WM capacity.

Overall, while the findings from NP tasks are susceptible to alternative explanations, the data from a varied set of inhibition paradigms are consistent with the idea that inhibitory effects, whether beneficial to performance, as in the antisaccade and Stroop tasks, or detrimental to performance, as in the NP paradigm, are dependent on a limited pool of controlled attentional resources.

Conclusion

The literature on selective attention shows that hybrid theories (e.g. Lavie, 1995) offer a compelling resolution to the debate between early and late selection on the extent to which distractors are perceived. The empirical evidence demonstrates that when perceptual load is low, distractors are perceived and identified, creating a need for active inhibition of responses towards these distractors. The existing evidence for active inhibition in selective attention, coming from the NP paradigm, has proved equivocal, as additional processes (e.g. episodic retrieval) have been implicated in addition to inhibition. The aim of this thesis is to establish new evidence for inhibition in selection by engaging response inhibition in one task and examining the effects this has on distractor rejection in another.

General methodological approach and overview

In the present research, the efficiency of distractor rejection under various test conditions was measured using the Eriksen flanker task. In the paradigm we used, response inhibition was engaged in Task 1, so that in the subsequent flanker task (Task 2) we could assess the effects of engaging inhibition on distractor rejection. We manipulated response inhibition using the stop-signal task (chapter 2), a spatial S-R mapping task (chapters 3 and 5) and the Stroop task (chapters 4 and 5).

In chapter 2, we sought to establish the basic predicted effect using the stop-signal task. Comparing stop trials with go trials, we examined whether the engagement of inhibition in the stop trials would lead to less efficient distractor rejection in the flanker task than on the go trials, where inhibition was not engaged. By reversing the ratio of stop trials to go trials between Experiments 1 and 2, we examined whether the relative frequency of either trial type might account for the observed results. Also, by examining the effects of whether or not a response was ever required in task 1, we attempted to dissociate the effects of inhibition from the effects of response execution (Experiment 3).

In chapter 3, we examined whether the suggestions of chapter 2 would generalise to another inhibition paradigm. We used a spatial S-R mapping task that involved congruent and incongruent S-R mappings. The literature on such tasks suggests that incongruent trials involve the inhibition of spatially congruent responses. We thus compared distractor interference following incongruent and congruent trials, and predicted greater distractor interference after incongruent responses, which involve inhibition, than after congruent responses, which do not.

This task also permitted us to further dissociate the effects of inhibition from the effects of response execution by nature of its requirement to inhibit one response while executing another. In this chapter we also manipulated the response-stimulus interval between the first and second tasks in our paradigm, in order to examine the time-course of the effects of engaging inhibition in one task on distractor rejection in a subsequent task.

In chapter 4, the Stroop task was employed as another inhibition paradigm, and a further means of examining the extent to which our findings would generalise across different inhibition tasks. The Stroop task was used in both its standard colour-naming form and its reversed word-reading form. In this way, we sought to dissociate the effects of congruency in the stimulus from the effects of inhibition, as both task types involve a congruency manipulation, but only the colour-naming task requires inhibition of the dominant response to the word, whereas the word reading task does not normally involve a strong tendency to respond to the colour.

Also in this chapter, we investigated whether flanker effects might always be greater following a more difficult task, as inhibition trials were generally found to be more difficult than no-inhibition trials – nowhere more so than in the Stroop task. Using a masking technique in a word-reading task (Experiment 8), and a colour discrimination task (Experiment 9), we investigated the effects of a manipulation of task difficulty that did not engage inhibition.

In the final empirical chapter, chapter 5, we sought to confirm the nature of the selection mechanism under investigation. More specifically, we sought to demonstrate that the effects of inhibition on selective attention were restricted to situations of low perceptual load, in which previous research has shown that distractors are perceived and an active means of selection is necessary. Thus, we looked to confirm that engaging inhibition in one task would have little or no effect on distractor rejection in a subsequent flanker task with high perceptual load.

CHAPTER TWO

Carry-Over Effects of Performing a Stop-Signal Task on the Efficiency of Selective Attention

Introduction

As described in the general introduction, the stop signal paradigm involves the presentation of a target stimulus followed on some trials by a signal that requires subjects to suppress responses to the target stimulus. As also discussed in the general introduction, our aim in the present study was to engage response inhibition in one task, and to gauge the effects on distractor rejection in a subsequent flanker task. In the present study, the stop-signal paradigm was used as a means to engage inhibition of response tendencies, and we compared performance in the flanker task after 'go' trials with performance after successful 'stop' trials. The evidence suggesting that this paradigm involves active response inhibition will now be discussed.

Evidence for inhibition of prepared responses in the stop signal paradigm

Performance in stop-signal tasks has been modelled in terms of a race between two independent processes: the go process and the stop process (Logan, 1981; Logan & Cowan, 1984; Logan, Cowan & Davis, 1984). The go process begins at the onset of the go target, and finishes with the execution of the response to the stimulus, while the stop process begins with the onset of the stop signal, and ends when the response is stopped. Whichever process wins the race (i.e. is completed first) determines whether the response is executed or stopped (Logan & Cowan, 1984; Osman, Kornblum & Meyer, 1986, 1990). The race model claims that stop-signal inhibition acts against responses which are actively progressing toward execution. The race model has become the standard view of the processes underlying performance in the stop-signal task. Evidence in support of the race model has come from numerous stop-signal studies which demonstrate that RTs on failed inhibition trials (i.e. stop-signal trials where stopping was unsuccessful) are shorter than RTs on go trials (De Jong, Coles, Logan & Gratton, 1990; Jennings, Van der Molen, Brock, & Somsen, 1992; Lappin & Eriksen, 1966; Logan, 1981; Logan & Cowan, 1984; Osman, Kornblum & Meyer, 1986, 1990). This finding suggests that on stop signal trials, preparation of responses to the task stimulus proceeds in the same way as on go trials, with the faster responses winning the race with the stop process and escaping inhibition, and the slower responses losing the race and being inhibited.

A further indication that responses are prepared and then inhibited on successful stop trials is the observation that mistakenly executed responses on signal trials (i.e. failed inhibition trials) increase in mean RT as the stop-signal delay is increased (De Jong et al., 1990; Jennings et al., 1992; Logan, 1981; Logan & Cowan, 1984; Osman et al., 1986). This is consistent with the idea that an increase in the stop-signal delay allows the go process a head-start in the 'race', thus allowing responses with slower RTs to escape inhibition. Accordingly, an increase in stop-signal delay also leads to a greater probability of failed inhibition (Logan & Cowan, 1984; Logan et al., 1984; Osman et al., 1986, 1990), suggesting that a greater proportion of the go-RT distribution falls before the finishing point of the stop process.

The characteristics of performance in the stop-signal task, as revealed by these findings, and as predicted by the race model, strongly suggest that the stop-signal task involves inhibition of responses that are prepared and initiated and indeed only successfully inhibited if the stop process reaches completion before they do.

As well as the inferences that have been made from reaction times, there is also somewhat more direct evidence that responses are initiated before inhibition in the stop-signal paradigm. Investigations into the 'point of no return' have shown that responses can reach a very advanced stage and yet still be inhibited before completion. The point of no return refers to a hypothetical stage of response processing at which responses become ballistic and cannot be prevented from reaching completion. Jennings et al. (1992) found that responses showing evidence of initiation at the stage of muscle activation, measured via electromyogram (EMG), could nonetheless be successfully inhibited. Other studies have demonstrated that responses that reach the stage of observable movement (e.g. a partial squeeze of a dynamometer: De Jong, Coles, & Logan, 1995; a partial elbow extension: McGarry & Franks, 1997) can still be inhibited before the movement is complete. The implication of these findings are that the stop signal paradigm clearly involves active inhibition of responses that are prepared and in some cases even partly initiated, as opposed to inhibition at another level such as representations of objects or locations.

Previous studies relating stop-signal inhibition and distractor rejection

Three previous studies have directly investigated the idea that the inhibition involved in stopping responses in the stop-signal task and go/no-go tasks is related to the putative involvement of inhibition in selective attention. Tipper, Weaver, Cameron, Brehaut & Bastedo (1991, experiment 4) placed a go/no-go task in between the prime and probe trials of a negative priming task. In the go/no-go task, subjects responded with the space bar to a letter "E", and made no response to a digit "7". Tipper et al. found no difference in the level of NP between trials with a go task and trials with a no-go task between prime and probe. As NP is typically taken to involve distractor inhibition, this finding may appear to be discouraging for our hypothesis that distractor inhibition should be affected by whether inhibition is engaged in stopping a response or not. However, it is likely that the go/no-go task in Tipper et al.'s study did not involve a strong requirement for inhibition. As the go and no-go stimuli retained their response assignments throughout the experiment, the no-go stimulus ("7") was never associated with a response. It is therefore highly likely that subjects simply did not generate response tendencies on no-'go' trials, and that there was therefore no need for inhibition.

Kramer et al. (1994) used a flanker task (Eriksen & Eriksen, 1974) followed by a stop signal on 25% of trials. In these 'stop' trials they found that estimates of stop-signal RT were greater, and the success of stopping was lower, in the incompatible-flanker condition than in either the compatible or neutral conditions. This difference in estimated stop-signal RT was replicated by Ridderinkhof et al. (1999), who also found that trials with a greater flanker compatibility effect were more likely to involve a failure to stop than trials with a smaller flanker effect.

The impaired stopping performance on incompatible vs. compatible flanker trials is encouraging for our suggestion that distractor processing should interact with processes involved in stopping responses. However, these findings may simply indicate that it is more difficult to stop a response on an incompatible trial because on such trials two responses are activated (one to the target and one to the distractor). Also, a 'pure activation' view of selection (e.g. Neisser & Becklen, 1975) wherein target information is selected by means of extra activation, would predict that a target representation on an incompatible trial would receive a boost in activation to allow it to compete successfully with the distractor for selection. A response to this more strongly activated target representation would therefore be more difficult to stop than a response to a less strongly activated target on a compatible trial. Thus, these results cannot be unambiguously attributed to the occurrence of inhibition in the flanker task, highlighting the need to approach this issue using a different methodology to those discussed.

Experiment 1

In Experiment 1, we employed a stop-signal task followed by a flanker task. In the stop-signal task, participants were required to perform a simple RT task, pressing the same specified key upon appearance of a shape (a white rectangle). On 25% of trials, however, the simple RT target was followed by a stop signal (a red circle) instructing subjects to withhold their response. In order to obtain a high percentage of successful inhibition in 'stop' trials, a single, short stop-signal delay was used.

This task was followed by the flanker task, in which participants were required to make a fast and accurate choice response to either an 'x' or a 'z' target. Simultaneously with the target there appeared a peripheral distractor letter above or below the centre of the display. This distractor was either compatible with the target letter (e.g. an 'X' distractor for an 'x' target), or incompatible with it (e.g. a 'Z' distractor for an 'x' target). Participants were instructed to ignore this irrelevant distractor throughout the experiment, and the extent of their success in ignoring the distractor was assessed by comparing RTs between incompatible and compatible trials. The extent to which incompatible RTs show interference was used as a measure of the efficiency of distractor rejection. Greater interference indicated less efficient suppression of responses to distractors.

Our main interest was in whether distractor effects in the flanker task differed following successful ‘stop’ trials and following ‘go’ trials. Our prediction was that if selective attention relies on a limited-capacity mechanism of response inhibition, then the engagement of response inhibition on ‘stop’ trials would reduce the capacity available for distractor rejection in the subsequent flanker task. We thus expected greater distractor effects in ‘stop’ trials than in ‘go’ trials.

As mentioned in the general introduction, the two tasks in our paradigm were performed with different hands so as to ensure that any interaction between them occurs at a cognitive, rather than motoric, level. Also, we compared successful ‘stop’ trials with ‘go’ trials instead of comparing successful and failed ‘stop’ trials because on trials in which subjects fail to stop in response to a signal, the subjects are likely to detect that they have committed an error. Trials with errors are known to affect RTs on subsequent trials or tasks (e.g. Rabbitt & Rodgers, 1977). In addition, it is not clear that inhibition mechanisms are not engaged at least in part on failed ‘stop’ trials. Thus, the comparison between stop and ‘go’ trials was seen as a cleaner comparison of levels of response inhibition.

Method

Subjects 14 students from the University of London, aged between 18 and 30, took part in the experiment for £5 payment. All had normal or corrected-to-normal vision. 5 subjects made incorrect responses on more than 35% of ‘stop’ trials, and were replaced with 5 new subjects. This was important in order to ensure that we gathered a workable amount of data from 'stop' trials, given that they comprised only 25% of all trials, and that they are crucial to the issues under investigation

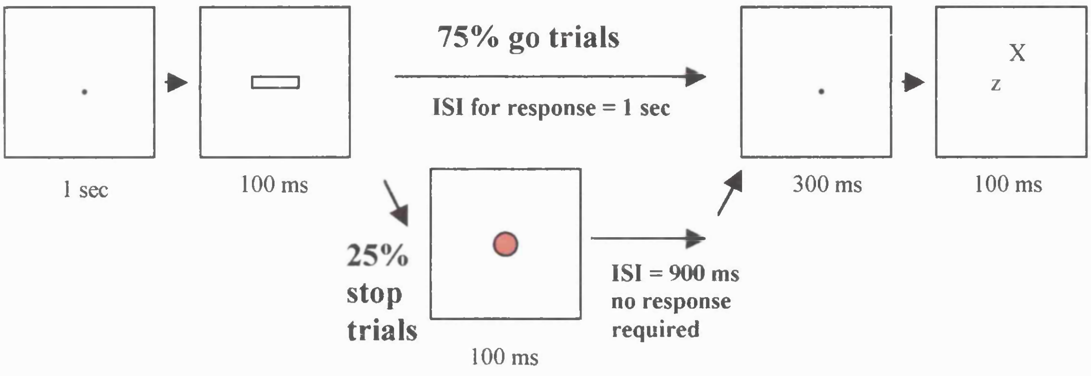


Figure 1. Stimulus sequence and presentation times in Experiment 1

Stimuli and Apparatus An IBM compatible computer attached to a VGA colour monitor presented the stimuli and recorded and timed the responses. The software used for creating and running the experiment was Micro Experimental Laboratory (MEL), version 2. A custom-built viewing hood kept subjects' eyes 60 cm from the computer screen. A schematic representation of the stimuli and procedure is shown in Figure 1. All stimuli were presented in a light grey colour (7 on the MEL colour palette) on a black background, unless otherwise specified. A fixation dot was presented in the centre of the screen before each task. The target stimulus in the stopping task was an unfilled rectangle subtending a visual angle of 5° horizontally and 0.75° vertically, presented at fixation. On 'stop' trials, a red circle with a diameter of 0.57° was presented at fixation as a stop signal. The target stimulus in the flanker task was a lower-case letter ('x' or 'z'), subtending a visual angle of 0.38° horizontally and 0.67° vertically. The target was presented equally often at one of six positions spaced 0.65° apart in a horizontal row at the centre of the display. An upper-case distractor letter ('X' or 'Z'), subtending 0.48° horizontally and 0.95° vertically, was also presented 1.9° above or below the centre. The distractor was equally likely to be compatible (e.g. an 'X' distractor for an 'x' target) or incompatible (e.g. a 'Z' distractor for an 'x' target) with the target. Using all possible combinations of target position, target identity, distractor position and distractor compatibility, 48 flanker task displays were created.

Procedure As can be seen in Figure 1, each trial began with the presentation of a fixation dot in the centre of the screen for 1 sec. This was followed by the stopping task, in which a target rectangle appeared at fixation for 100 ms. Subjects were required to respond to the rectangle by pressing the 's' key on the computer keyboard as rapidly as possible with their left index finger unless a stop signal was presented. Subjects had 1 second in which to make their 'go' trial response. This time window elapsed whether or not a response was made. Then, a second fixation dot appeared for 300 ms, followed by the flanker task display, which was presented for 100 ms. Subjects were required to respond to the targets by pressing the '2' key on the numeric keypad for an 'x' target, and the '0' key for a 'z' target. They were requested to make their responses as rapidly as possible while avoiding errors. Subjects were also instructed to ignore the distractor letter, and were informed about its possible detrimental effect on performance if it was not ignored. Subjects were provided with a two-second interval for these choice responses, and this interval elapsed before the start of the next trial regardless of whether a response was made. If a response was missed, or an incorrect response made on either task, a 100-ms tone was given as error feedback at the end of the trial. On 25% of trials, a stop signal was presented for 100 ms immediately after the rectangle target of the stopping task. Upon seeing a stop signal, subjects were required to withhold their responses to the rectangle. Any responses made within the subsequent interval of 900 ms were recorded as errors.

Each subject performed 4 experimental blocks of 96 trials each of which 25% were 'stop' trials. Subjects initiated each block by pressing the space bar. Each block consisted of a random mix of 24 'stop' trials: 12 compatible and 12 incompatible; and 72 'go' trials: 36 compatible and 36 incompatible. Each block consisted of 2 sets of the 48 variations of the flanker task displays. The allocation of half of the set to the 24 'stop' trials was counterbalanced between blocks. Thus in each pair of consecutive blocks, all 48 displays were used; once in the 'stop' trials, and three times in the 'go' trials. A practice block of 24 trials, the results from which were excluded from the analysis, preceded the experimental blocks.

Results

Stopping task Go trial RTs ranged from 206 ms to 598 ms between subjects. The average RT across subjects was 452 ms. There were very few failures to respond on 'go' trials ($\underline{M}$ = 1.1%). The average rate of failures to stop on 'stop' trials was 14.6%.

Flanker task Table 1 presents the group mean RTs and error rates on the flanker task as a function of trial type (stop, go) and distractor compatibility (incompatible, compatible). Trials with errors on either the stopping or flanker task were excluded from the RT analysis. A 2 x 2 repeated measures ANOVA was run on the RTs with the variables of distractor compatibility and trial type. This analysis confirmed a main effect of compatibility: RTs were longer in incompatible trials than in compatible trials, F(1,13) = 25.83, $p < .001$, indicating a failure to ignore the distractors. This was expected given the low level of perceptual load in the displays (see Lavie, 1995; Lavie & Cox, 1997). There was also a main effect of trial type, F(1,13) = 9.66, $p < .01$, indicating slower responses after successful stops than after 'go' responses, in line with previous reports of generalised slowing after 'stop' trials (Rieger & Gauggel, 1999). More importantly, there was an interaction between trial type and compatibility, F(1,13) = 6.53, p = .024. This interaction indicates that, as predicted, distractor effects were greater after a successful stop than after a 'go' response (see Table 1). A similar ANOVA on the error rates did not reveal any significant effect ($p > .10$ in all comparisons).

Table 1 Mean Reaction Times (in ms, standard errors in parentheses) and Error Rate (%) Across Subjects (n=14) as a Function of Distractor Compatibility and Trial Type in Experiment 1

	Distractor condition				Effect size	
	I		*C*		*I-C*	
Trial type	RT	%E	RT	%E	RT	%E
Go	684 (47)	4	635 (38)	5	49 (12)	-1
Stop	726 (49)	4	645 (40)	6	81 (16)	-2

Note. I = Incompatible; C = Compatible.

The greater distractor effect in 'stop' trials is unlikely to be attributable to scaling due to slower RTs after 'stop' trials, as it remained significantly greater than the distractor effect after 'go' trials when calculated as the proportion of the overall RT per individual in each condition. The distractor interference effect was 12% of the mean overall RT after a stopped response and 7% of the mean overall RT after a go response, and this difference was significant, t(13) = 2.33, p < .05.

Discussion

Distractor effects in the flanker task were greater in 'stop' trials, when a response was successfully stopped in Task 1, than in 'go' trials, when a response was executed in Task 1. These findings confirm our prediction that the engagement of response inhibition in Task 1 reduced subjects' ability to efficiently reject irrelevant distractors in a subsequent selective attention task. Thus the results from Experiment 1 provide preliminary support for the hypothesis that distractor rejection in situations of low perceptual load relies on a mechanism of active inhibition.

The present findings are consistent with previous findings showing that stop-signal inhibition and distractor interference effects can interact, as demonstrated by less efficient stopping of responses to flanker-task targets in incompatible vs. compatible flanker conditions (Kramer et al., 1994; Ridderinkhof et al., 1999). However, the findings of these authors are susceptible to the criticism that stopping responses in the flanker task in incompatible distractor conditions may be more difficult because two separate responses may be activated (one to the target and one to the distractor, as mentioned previously). This criticism does not apply to the present findings, as they show the effects of stopping Task-1 responses on distractor rejection in the subsequent flanker task.

Our comparison of 'stop' and 'go' trials showed an increase in RTs (in 'stop' trials) to compatible displays as well as incompatible displays, which might suggest that the observed increase in distractor effects is primarily due to an increase in interference from incompatible distractors. However, as there was a main effect of Task 1 trial type, such that flanker task responses were generally slower after a stopped response than after a go response, this general slowing effect across both flanker compatibility conditions could obscure the observation of any potential increase in facilitation from compatible flankers.

In general in this thesis, we do not intend to draw strong conclusions from the individual contributions of the two distractor compatibility conditions to the flanker effect. Previous studies involving the flanker task have shown an inconsistent pattern in the effects of identical compatible distractors, with some studies finding them to cause facilitation (Eriksen & Eriksen, 1979; Eriksen, Gottel, St. James & Fournier, 1989; Flowers & Wilcox, 1982; Grice, Canham & Gwynne, 1984; Miller, 1982) and others finding them to cause interference (Bjork & Murray, 1977; Estes, 1972; Santee & Egeth, 1982). Our hypothesis concerned the size of the distractor effect as a whole, as an overall measure of selection efficiency, rather than narrower hypotheses about the individual patterns of performance in compatible and incompatible trials. As a whole, the ability to reject distractors efficiently was impaired in 'stop' trials.

There are, however, alternative accounts that may explain the present finding of a larger distractor effect after a successful stop than after a response. In addition to their different response requirements, the 'stop' and 'go' trials differed in their frequency of occurrence (25% for ‘stop’ trials, 75% for ‘go’). It is possible that this difference in probability of different trial-types, rather than the occurrence of response inhibition, is the cause of larger distractor effects. In one of Tipper, Weaver, Cameron, Brehaut & Bastedo (1991)’s experiments (expt 5), a go/no-go task was interpolated between the prime and probe trials of a negative priming task, with 25% go and 75% no-’go’ trials in one group, and 75% go and 25% no-’go’ trials in another group. In both groups of subjects, there was a trend for less NP in the 25% condition (be it go or no-go) than in the 75% condition. Although this difference was only significant in the 25% no-go group, the overall trend raises the possibility that relatively infrequent events are more likely to disrupt performance in concurrent selective attention tasks.

If infrequent events were to have a larger effect on selective attention mechanisms than frequent events, this could be due to the involvement of control functions other than inhibition in the control of selective attention (see Lavie, 2000). It has been repeatedly demonstrated that patients with lesions in the frontal lobes, who typically suffer from deficits in cognitive control functions (e.g. Shallice, 1988), have difficulty performing tasks that involve responding to novel or unexpected situations. For example, frontal patients have difficulty performing ‘cognitive estimation’ tasks (Shallice & Evans, 1978) in which existing knowledge must be used in unexpected ways, and on the Hayling sentence-completion task (Burgess & Shallice, 1996), in which a sentence must be completed with one word such that it makes no sense. Moreover, frontal patients have been shown to lack the large anterior P300 EEG response shown by normals when an unexpected stimulus is presented in a tone discrimination task (Knight, 1984), suggesting that the damaged frontal areas are crucial for processing unexpected events. Thus it seems plausible that the infrequent stop signals engage frontally-located control mechanisms that are specialised to deal with relatively unexpected situations, and it is these control mechanisms, rather than inhibition mechanisms, that reduce the efficiency of rejecting irrelevant distractors.

In Experiment 2, we examined this possibility by reversing the ratio of 'stop' to 'go' trials, putting 'go' trials in the minority at 25%.

Experiment 2

In order to test the possibility that the results of Experiment 1 were due to the ratio between the 'stop' and 'go' trials, as opposed to the inhibition involved in stopping, Experiment 2 involved a flanker task preceded by a stopping task with 75% 'stop' trials and 25% 'go' trials. 'Go' trials were indicated by a green 'go' signal, and 'stop' trials had no signal. Subjects therefore only had to respond to the rectangle when it was immediately followed by a 'go' signal. If any infrequent event will lead to greater distractibility, that is: if the relative frequency of 'stop' to 'go' trials was chiefly responsible for the results of Experiment 1, then we should again find greater distraction in the trials constituting 25% of the experiment, (now the 'go' trials). However, if, as we hypothesised, loading a central inhibition mechanism by the requirement to suppress responses results in greater failure to suppress responses to distractors in a subsequent selective attention task, then we should again find greater distractor effects after a successful stop than after a response.

Method

Subjects 14 students from University College London, aged between 18 and 30, took part in the experiment for £5 payment. All had normal or corrected-to-normal vision. None of these subjects had participated in Experiment 1.

Stimuli & Procedure Experiment 2 involved the same stimuli and procedure as Experiment 1, with the following differences: Instead of a red 'stop' signal, 25% of trials had a green 'go' signal of the same dimensions, to which subjects responded by pressing the 's' key on the computer keyboard. The remaining 75% of trials had no signal and subjects were instructed to withhold their response to the rectangle on these trials.

Although the 'go' trials were now more rare, subjects were instructed to respond to the rectangle as fast as possible upon seeing the green 'go' signal. There were 4 blocks of 96 trials, preceded by a practice block of 24 trials, the results of which were excluded from the analysis. The timings of the stimuli were identical to those displayed in Figure 1, with the exception of the ISI between the 'go' signal and the 2nd fixation dot. This was increased from 900 ms to 1000 ms in order to maintain a 1000 ms interval between the Task 1 stimulus and the flanker stimuli on 'stop' trials (which now do not feature a 100 ms signal), as was the case in Experiment 1.

Results

One subject had abnormally large distractor effects (an individual mean of 271 ms; group mean 79 ms) in the flanker task, and was replaced by a new subject.

Stopping task Trials with errors on this task were excluded from the RT analysis. The across-subjects mean RT to 'go' trials in Task 1 was 446 ms. Individual mean RTs ranged from 348 ms to 546 ms. There were again very few failures to respond on 'go' trials (M = 1%; range = 0% to 4%), and virtually no false positive responses on 'stop' trials.

Table 2 Mean Reaction Times (in ms, standard errors in parentheses) and Error Rate (%) Across Subjects (n=14) as a Function of Distractor Compatibility and Trial Type in Experiment 2

	Distractor condition				Effect size	
	I		*C*		*I-C*	
Trial type	RT	%E	RT	%E	RT	%E
Go	754 (56)	10	696 (44)	5	58 (17)	5
Stop	766 (53)	9	694 (43)	4	72 (17)	5

Note. I = Incompatible; C = Compatible.

Flanker task Table 2 presents the group mean RTs and error rates on the flanker task as a function of trial type and distractor compatibility. Trials with errors on either the stopping or flanker task were excluded from the RT analysis. A 2 x 2 repeated measures ANOVA was run on the RTs with the factors of distractor compatibility (incompatible or compatible) and trial type ('stop' or 'go'). This analysis confirmed a main effect of compatibility, F(1,13) = 19.65, p = .001. RTs were longer in incompatible trials than in compatible trials, indicating a failure to ignore the distractors. As in Experiment 1, this was expected given the low level of perceptual load in the display (e.g. Lavie, 1995). Unlike Experiment 1, there was no main effect of trial type, F < 1, in this experiment (across-subject mean RTs were 630 ms in the 'stop' trials and 625 ms in the 'go' trials). Crucially, there was an interaction between trial type and compatibility, F(1,13) = 4.65, p = .05. This interaction indicates that, as before, there was a greater compatibility effect on 'stop' trials than on 'go' trials.

A similar ANOVA on the error rates showed a main effect of compatibility, F (1,13) = 9.47, p = .009. There were more errors in the incompatible than the compatible trials, replicating the RT results (see Table 2). The error rates and distractor effects in errors were the same for 'go' and 'stop' trials, as indicated by the lack of a main effect of trial type, F < 1, or an interaction, F < 1.

Between experiments comparison

In order to assess whether the frequency of stop trials any difference to the effect of Task 1 condition on flanker compatibility, the data from Experiments 1 and 2 were compared statistically.

Task 1 A 2 x 2 mixed-model ANOVA was performed on the error rates, with Task-1 condition (stop vs. go) as a within-subjects variable, and experiment as a between-subjects variable. The interaction between Task-1 condition and experiment was significant, F(1,27) = 36.821, p< .001. This reflects the fact that, as reported above, Task-1 errors were more frequent in stop vs. go trials in Experiment 1, while there was no such difference in Experiment 2. An independent samples t-test on the RTs revealed no differences between experiments, t(27) = .437.

Flanker task A 2 x 2 x 2 mixed-model ANOVA was performed on the flanker task RTs, with Task-1 condition (stop vs. go) and flanker compatibility as within-subjects variables, and experiment as a between-subjects variable. The 3-

way interaction among Task-1 condition, experiment and flanker compatibility was not significant, F(1,27) = 1.71, p = .202, showing that the effect of stopping in Task 1 on the flanker effect was not affected by the frequency of stop trials. This suggests that the effect of stopping responses on the efficiency of distractor rejection in a subsequent task is the same regardless of the frequency of stop trials. Although there was a numerical trend for a greater main effect of Task-1 condition on flanker task RTs (with slower RTs on stop trials than go trials) in Experiment 1 (27 ms) than in Experiment 2 (5 ms), this interaction between Task-1 condition (stop vs. go) and experiment was not significant, F(1,27) = 3.503, p = .072. There was no interaction between flanker compatibility and experiment, F < 1.

A similar ANOVA on the error rates showed no 3-way interaction among Task-1 condition, experiment and flanker compatibility, F < 1. A significant interaction between Task-1 condition (stop vs. go) and experiment, F(1,27) = 38.417, p < .001, reflects the fact that flanker task responses were (numerically) less accurate in stop trials than in go trials in Experiment 1, while the reverse was (numerically) the case in Experiment 2. As reported above, neither of these main effects were significant individually. Finally, a significant interaction between experiment and flanker compatibility, F(1,27) = 6.028, p <.05, reflects the fact, also already reported, that there were significantly more errors in the incompatible than the compatible trials in Experiment 2, while there was no main effect of compatibility in Experiment 1.

Discussion

Experiment 2 replicated the results of Experiment 1, again showing greater distractor effects after a successful stop than after a response. Given that the frequency of ‘stop’ trials was 75% in this experiment, and 25% in the previous experiment, the results of these experiments together rule out any frequency-based account for the effects of ‘stop’ trials on distractibility in our task. Instead, Experiment 2 provides further support for our hypothesis that effective rejection of perceived distractors depends on the availability of inhibitory functions. Note also that Experiment 2 involved signals on ‘go’ trials, rather than on ‘stop’ trials as in Experiment 1. Thus the occurrence of a signal after the stimulus cannot itself be responsible for the greater distractor effects in ‘stop’ trials in Experiment 1.

It should also be noted that despite the lower probability of ‘go’ trials in this experiment, responses in Task 1 were of a comparable speed to ‘go’ trial responses in Experiment 1 (M = 446 ms in Experiment 2; M = 452 ms in Experiment 1). This suggests that in spite of the relative infrequency of ‘go’ trials, response preparation still reliably occurred upon presentation of the Task 1 stimulus. However, the negligible amount of responses on ‘stop’ trials (i.e. failures to inhibit) in Experiment 2, compared to the 15% level in Experiment 1, suggests that response preparation in Experiment 2 may have taken the form of a general readiness to respond (i.e. a response tendency) rather than actual response initiation.

Experiment 2 thus provides further support for our view that central inhibition functions are involved both in stopping responses in a stop signal task and in suppressing response tendencies to an irrelevant distractor. However, the results of the first two experiments are still open to another alternative account in terms of the different response-execution requirements of ‘stop’ and ‘go’ trials. The ‘go’ trials involved the execution of a key-press response, while the ‘stop’ trials did not. Thus it could be that distractor effects are always greater after no response is made than after a response. For example, some accounts of action selection propose that for a particular response to be selected over other potential responses that rely on overlapping resources, lateral inhibition between potential responses is necessary (e.g. Cooper, 2002; Cooper & Shallice, 2000; Houghton & Tipper, 1996). Thus, perhaps executing a response in Task 1 of this paradigm involves some lateral inhibition of other potential responses including that towards a distractor in the next task. Distractor effects may be smaller after a response was made than after no response due to such processes of lateral inhibition.

Note, however, that this account would also predict inhibition of responses to the target in the next task, and thus slower responses in general after a response has just been executed than after no response to Task 1. Our results did not show this pattern. In fact in Experiment 1, flanker-task RTs were slower on 'stop' trials than on 'go' trials. Nonetheless it is important to rule out any potential alternative accounts of our results in terms of the different response execution requirements in the stop vs. 'go' trials. This was the purpose of Experiment 3.

Experiment 3

The purpose of Experiment 3 was to investigate the possibility that the results of Experiments 1 and 2 were due to the different response execution demands of the 'stop' and 'go' trials, as opposed to the inhibition involved in stopping. Thus we compared flanker task performance after a response and after no response as before, however in this experiment, making no response should not have involved inhibition. Subjects performed a block of trials in which they were required only to respond to the flanker task; Task 1 stimuli required no response – an instruction repeated to subjects before each block. The colour of the rectangular target in these 'no-go' blocks was different from that of the rectangular target in 'go' blocks, to further discourage any response tendencies. As a response to this different-coloured stimulus is never required from the subject, no response tendency should be elicited by it, and thus no inhibition is required to prevent responses.

Subjects' responses in 'no-go' blocks were compared to their responses in blocks in which both the flanker task and Task 1 both always required a response. If distractor effects are always greater after a null response than after a response has just been executed, that is: if the different demands on response execution of 'stop' and 'go' trials were chiefly responsible for the results of Experiments 1 and 2, then we should again find greater distraction in the condition with no key press preceding the flanker task. If distractor effects are only greater after a null response which involves inhibition of a response, as we claim, then distractor effects should not differ between trials that involve a response and trials that do not involve a response but also do not involve inhibition.

Method

Subjects 13 students from the University of London, aged between 18 and 30, took part in the experiment for £5 payment. All had normal or corrected-to-normal vision. None of these subjects had participated in Experiment 1 or 2. One subject's error rate in the go/no-go task was 34%, and this was more than two standard deviations from the group mean (group mean = 6%; SD = 9%). This subject was replaced with a new subject.

Stimuli & Procedure Experiment 3 involved the same stimuli, timing and procedure as the 'go' trials in experiment 1, with the following differences: There were no signals in any of the experimental conditions. The experiment was divided into blocks in which the rectangle appeared in light grey, and subjects were to respond to it with the 's' key on the computer keyboard ('go' blocks), and blocks in which the rectangle appeared in red, and subjects were required not to respond to it ('no-go' blocks). The sequence of events was thus identical to that represented in the 'go' trials in Figure 1.

The experiment consisted of 4 consecutive blocks of one condition, and then 4 consecutive blocks of the other condition. Half of the subjects began with the 'go' blocks, and the other half began with the 'no-go' blocks. For each condition, subjects performed a practice block of 24 trials before embarking on 4 consecutive blocks of 72 trials. A screen instructing subjects how to respond to the task stimuli appeared at the start of each block.

Results

Go/no-go task The across-subjects mean RT to the rectangle in 'go' blocks was 293 ms. This is shorter than the mean RTs in the go trials of Experiment 2 (M = 446 ms) and Experiment 1 (M = 452 ms). This was expected given that go responses in the previous experiments were intermixed with stopped responses thus requiring more control over each response that is made. Perhaps also some of the go responses in the go blocks were anticipatory, as the rectangle was always presented and such anticipatory responses would have no apparent cost to performance.

Individual mean RTs ranged from 232 ms to 457 ms. The mean rate of misses on 'go' blocks was 3.5%. However, this may reflect anticipatory responses (with RTs less than 100 ms) made during the presentation of the rectangle, which would not have been recorded by the computer. Individual mean error rates ranged from 1% to 14%. There were no false positives on 'no-go' blocks, as was expected given that the red rectangle was not associated with a response.

Flanker task Table 3 presents the group mean RTs and error rates on the flanker task as a function of block type and distractor compatibility. Trials with errors on either the go/no-go task or the flanker task were excluded from the RT analysis. A 2 x 2 repeated measures ANOVA was run on the RTs with the factors of distractor compatibility (incompatible or compatible) and block type ('go' or 'no-go'). This analysis confirmed a main effect of compatibility, F(1,12) = 40.49, p < .001. RTs were longer in incompatible trials than in compatible trials, indicating that as before subjects failed to ignore the distractors. There was no main effect of block type, F(1,12) = 2.82, p > .10, in this experiment (across-subject mean RTs were 453 ms in the 'no-go' blocks and 475 ms in the 'go' blocks). Crucially, in contrast with Experiments 1 and 2, there was no interaction between block type and compatibility, F < 1. As can be seen in Table 3, the distractor compatibility effects were very similar across 'go' and 'no-go' blocks: 39 ms in 'go' blocks, and 36 ms in 'no-go' blocks. Thus, as predicted, the requirement to make or not make a response in Task 1 made no difference to the distractor effect in the flanker task.

Table 3 Mean Reaction Times (in ms, standard errors in parentheses) and Error Rate (%) Across Subjects (n=13) as a Function of Distractor Compatibility and Block Type in Experiment 3

	Distractor condition				Effect size	
	I		*C*		*I-C*	
Block type	RT	%E	RT	%E	RT	%E
Go	594 (33)	4	555 (31)	2	39 (5)	2
No-go	571 (33)	4	535 (28)	1	36 (8)	3

Note. I = Incompatible; C = Compatible.

A similar ANOVA on the error rates showed a main effect of compatibility, F(1,12) = 16.80, p = .001, with a greater number of errors in the incompatible than the compatible trials, but not of block type, F (1,12) = 1.13, p > 0.3. The interaction was not significant, F < 1.

Discussion

As predicted, in Experiment 3, distractor effects in the flanker task were equivalent regardless of whether or not a key-press response had been made before that task. In contrast to Experiments 1 and 2, this experiment involved entire blocks in which no response was required to the stimulus before the flanker task. Thus, in these 'no-go' blocks, there was never any requirement for response preparation (as supported by the lack of false positive responses), and therefore no requirement for inhibition when responses were not made. As the no-go responses in Experiment 3 did not involve inhibition, this experiment allows us to rule out the possibility that the simple lack of a response was responsible for the greater distractor effects found after stopped responses (vs. go responses) in Experiments 1 and 2 (for example in terms of lateral inhibition accounts as discussed in the introduction to this experiment). Thus far, our findings support the idea that inhibition is the crucial factor responsible for the modulation of distractor effects in Experiments 1 and 2.

Note that flanker task RTs were substantially faster overall in this experiment (M = 564 ms) than in Experiment 1 (M = 673 ms) or Experiment 2 (M = 728 ms), as well as average distractor effects being smaller (M = 38 ms) than in either Experiment 1 (M = 65 ms) or Experiment 2 (M = 65 ms). Even when just the 'go' conditions of the three experiments are compared, flanker task RTs are substantially faster in Experiment 3 (M = 575 ms) than in Experiment 1 (M = 660 ms) or Experiment 2 (M = 725 ms). This seems to indicate that the lack of a requirement for inhibition in Task 1 of Experiment 3 created an overall lower level of cognitive load than in Experiments 1 and 2, allowing more efficient performance of both tasks. However, as this improved efficiency is present in the both the comparison of 'go' trials between experiments and the comparison of no-go or stopped trials between experiments, it seems unlikely that an effect of general cognitive load is responsible for the difference between distractor effects in 'stop' and 'go' trials in Experiments 1 and 2, and the lack of such differences in Experiment 3.

Together, the three experiments in this chapter serve to establish initial support for our hypothesis that engaging response inhibition in one task leads to less efficient distractor rejection in a subsequent selective attention task. As such, they provide a promising suggestion of a new line of evidence that selective attention relies on active inhibition of irrelevant distractors. This is consistent with theories of selective attention which have emerged from the NP literature (e.g. Houghton, Tipper, Weaver & Shore, 1996; Houghton & Tipper, 1994, 1998; Neill, 1977; Tipper, 1985, 2001). In the next chapter, we attempt to generalise our findings to a different type of inhibition task, in order to provide converging evidence for the suggestions of this chapter. We also seek to address more conclusively the issue of the effects of response demands in Task 1, and to investigate the temporal characteristics of the effects of inhibition on selective attention in a subsequent task.

CHAPTER THREE

Carry-Over Effects of Performing a Spatial S-R Mapping Task on the Efficiency of Selective Attention

Introduction

Our primary aim in the present chapter was to examine whether the findings of Chapter 2 would generalise to a different means of manipulating inhibition. In contrast to the stop-signal paradigm, in which the effects of inhibition were compared between trials involving executed responses and trials involving no overt response, in this chapter we sought a paradigm in which the effects of inhibition are compared between two trial types which both involve executed responses. To this end, as Task 1 we used a task involving varied spatial stimulus-response (S-R) mappings. Specifically, we presented arrows pointing left or right and manipulated the congruency of responses to these arrows by asking subjects to make left or right key responses either in the direction of the arrow (congruent condition) or in the opposite direction (incongruent condition).

The literature on this paradigm suggests that when spatial stimuli (such as arrows) are mapped onto responses with a similar spatial arrangement, the spatially corresponding response is strongly activated by the stimulus, and must be suppressed on incongruent trials in order for the correct response to be made. Thus, successful execution of spatially incongruent responses is likely to involve inhibition whereas successful execution of congruent responses is not (as only the spatially congruent information, which produces no response conflict, is activated on such trials). This task can thus allow us to compare the effects of inhibition between congruent (no inhibition) and incongruent (inhibition) trials, both of which involve executed responses.

As incongruent trials involve the inhibition of one response and the execution of another, this tasks involves *selective* inhibition, as opposed to stopping tasks, in which inhibition is non-selective (i.e. a stop-signal indicates that *all* responses must be stopped, and none executed). There is a consensus that the locus of inhibition in such selective inhibition tasks is central (e.g. Band & Van Boxtel, 1999; De Jong et al., 1990, 1995). The likely central locus of the inhibition mechanisms involved is again encouraging for our hypothesis that this task will interact with a separate selective attention task. In the following sections I describe the evidence for the automatic activation of spatially corresponding responses in spatial S-R mapping tasks. This evidence strongly suggests that incongruent responses in such tasks involve suppression of the automatically activated congruent response.

Behavioural evidence for automatic activation of spatially congruent responses

The finding that responding to spatial stimuli is faster when the S-R mapping is congruent (e.g. left-hand response to left positioned stimulus) than when it is incongruent (e.g. right-hand response to left positioned stimulus) is very well established (e.g. Fitts & Seeger, 1953; Fitts & Deininger, 1954; Nicoletti, Anzola, Luppino, Rizzolatti & Umiltà, 1982; Proctor & Dutta, 1993). Spatial S-R congruency effects are found when the spatial information is task-relevant, as when subjects respond to the stimulus position (e.g. Fitts & Seeger, 1953; Fitts & Deininger, 1954; Shwartz, Pomerantz & Egeth, 1977; Heister & Schroeder-Heister, 1994), or task-irrelevant, as when subjects respond to another dimension of the stimulus such as colour or identity (e.g. Simon & Rudell, 1967; Simon & Small, 1969; Wallace, 1971; Hedge & Marsh, 1975; Simon, 1990; Hommel, 1995; Proctor & Lu, 1999; Zhang, 2000). For example, in the classic Simon task, subjects respond to the colour of a stimulus (e.g. a right-hand response for red, and a left-hand response for blue), and responses are typically faster when the position of the stimulus (which is irrelevant) corresponds with the position of the response hand (e.g. Simon, 1969).

The position of the stimulus in a typical Simon task may not be entirely irrelevant, as the consistent mapping of a particular stimulus colour with a particular response may form a strong association between the two, such that the stimulus position becomes part of the representation of the colour (e.g. "left" becomes associated with "red" – Hasbroucq & Guiard, 1991). Nevertheless, there is clear evidence that responses to the position of a stimulus in Simon tasks can be activated even if the spatial information is defined as irrelevant and both contained in a separate object and separated in time from the relevant information (Hommel, 1995). Hommel asked subjects to respond to the direction of a left or right-pointing central arrow, which was followed by a lateralised go/nogo signal 1 sec later. In this way, the irrelevant spatial information (the position of the signal) was not presented until *after* the relevant information was fully processed and a response was prepared. On 'go' trials, the results showed a clear effect of the congruency between the signal position and the side of the response despite the fact that the signal position was irrelevant to the task, and could not be associated with any of the targets as it was presented too late to interfere with target processing. This result provides strong support for the idea that the activation of spatially-congruent responses by stimuli with spatial information is automatic and unavoidable.

It may be that automatic activation of spatially corresponding responses occurs because of high *dimension overlap* between the stimulus and response sets. Higher dimension overlap is produced by similarity in content or structure between the stimulus and response sets (Kornblum, Hasbroucq & Osman, 1990). Similarity in content refers to whether or not the stimulus and response sets occur along related dimensions. An example of similarity in content would be if stimulus colour were responded to using coloured keys, as opposed to if stimulus colour were responded to with keys labelled with numbers. Similarity in structure refers to whether or not the stimulus and response sets are mapped to each other in a way that preserves the internal order of the two sets, regardless of the similarity in the content of the sets. An example of similarity in structure would be if progressively darker colours were mapped to keys arranged in a row, such that the darkest colour was mapped to the rightmost key, and the next darkest to the next key along, etc.

Another possible explanation for automatic response activation is that it occurs because representations of action-contingent events in the world (*action concepts)* provide a direct link between perception and action, such that the action concept for a right-hand response can be activated by the perception of a rightward-oriented stimulus (Hommel, 1997). Whatever the reason behind automatic activation of spatially corresponding responses, there must be some means by which such activated response tendencies are prevented from reaching execution.

Neural evidence for automatic activation of spatially congruent responses

Perhaps the strongest line of evidence that spatially incongruent responses involve activation of the spatially congruent responses (which thus need to be suppressed for the correct response to be made) comes from electrophysiological recordings. For example, recordings of Lateralised Readiness Potentials (LRPs), thought to index the relative activation in motor cortex of either hand used to respond (De Jong, Wierda, Mulder & Mulder, 1988; Gratton, Coles, Sirevaag, Eriksen & Donchin, 1988), provide a direct indication of whether or not a spatially corresponding response is activated.

De Jong, Liang & Lauber (1994) demonstrated that in a Simon task, where stimulus colours are mapped to left or right hand responses, activation of the response corresponding to the stimulus *position* is observed (via LRPs) on incongruent trials, despite the irrelevancy of stimulus position to the task. After this initial activation of the congruent response, De Jong et al.'s LRP data showed a change in the direction of the LRP, indicating subsequent activation of the correct, incongruent, response. This provides support for the proposal that performance of spatial mapping tasks involves two processes: initial automatic activation of the congruent response, and then suppression of this response to allow controlled implementation of the S-R mapping.

Eimer, Hommel & Prinz (1995) provided evidence that irrelevant spatial cues elicit automatic activation of corresponding responses (as indicated by LRPs from motor cortex) even when the cue is most likely to be misleading. Their task required subjects to respond to the position of a stimulus, using a congruent S-R mapping in one experiment and an incongruent mapping in another experiment. The likely target position was pre-cued by a central arrow, which indicated the subsequent target location with 75% validity in both experiments. Thus, even though the arrow was always a 75% valid cue of the *stimulus* position, it was only a 75% valid cue of the *response* position when the S-R mapping was congruent. When the incongruent S-R mapping was used, the arrow indicated the side *opposite* to that of the likely *response* on 75% of trials. In both experiments (and thus regardless of whether the arrow usually indicated the correct or incorrect response), Eimer et al. observed (via LRPs) activation of the response hand on the side indicated by the arrow 200 ms after its onset. Thus, response activation in the direction of the arrow was observed even when such a response was most likely to be incorrect, suggesting that the spatially corresponding response was activated automatically.

There is also evidence of automatic activation of spatially corresponding responses from further down in the response stream. Hasbroucq, Burle, Akamatsu, Vidal & Possamaï (2001) used electromyographic recording to measure muscle activity during a task in which subjects were required to respond congruently or incongruently (in blocks) to an LED which illuminated randomly on the left or right of fixation. Subjects responded with their left or right thumb, and the results showed that on correct incongruent trials muscle activity in the non-required thumb sometimes occurs before the required thumb muscle is activated, suggesting that on incongruent mapping trials the stimulus automatically elicits activation of the congruent response.

Electrophysiological recordings in the monkey have also demonstrated activity in motor cortex that suggests automatic activation of spatially corresponding responses. Georgopoulos, Lurito, Petrides, Schwartz & Massey (1989; see also Lurito, Georgakopoulos & Georgopoulos, 1991) trained rhesus monkeys on a task requiring them to turn a handle to match the position of an illuminated light in a circle of non-illuminated lights. When another light in the circle then came on, the monkey was to turn the handle toward this new position if the light was dim (congruent trials), and to turn the handle to a position 90° counter-clockwise to it if the light was bright (incongruent trials). Georgopoulos et al. found that on incongruent trials, the neuronal population vector in primary motor cortex (which has been shown to code the direction of the planned movement) initially pointed in the direction of the stimulus, and only later rotated to the correct direction of the response. This result suggests that the congruent response is activated automatically and must be overridden for the correct response to be made. Riehle, Kornblum & Requin (1997) used a similar procedure: monkeys had to turn a handle toward a light (i.e. a congruent response) if it was one colour, and away from it (i.e. an incongruent response) if it was another colour. They found that on incongruent trials, some neurons in primary motor cortex initially showed the pattern of activation associated with a congruent mapping, providing further neural evidence for the automatic activation of the spatially congruent response.

Experiment 4

The studies discussed converge on the suggestion that spatially congruent responses are activated automatically, and thus the process of responding correctly on incongruent trials requires inhibition of this activated congruent response. In Experiment 4 we employed a manipulation of spatial S-R congruency as Task 1, interleaved with the flanker task as in Experiments 1 and 2. In the spatial S-R mapping task, subjects were presented with a left or right-pointing arrow, followed by a signal which dictated the congruency of the stimulus-response mapping for that trial, and responses were made with a left or right key-press. The literature on spatial S-R congruency effects led us to expect that on incongruent trials the congruent response is automatically activated, and must be inhibited in order for the correct response to be made. We therefore predicted that the flanker effect would be greater after an incongruent response in Task 1 than after a congruent response in Task 1.

Method

Subjects 12 students, aged between 18 and 35, took part in the experiment for £5 payment. All had normal or corrected-to-normal vision, and none had participated in Experiments 1-3. One subject performed at chance level accuracy on the flanker task (individual mean error rate = 50%; group mean = 11%, SD = 12%), and another subject was unusually slow on the spatial task (individual mean RT = 769 ms; group mean = 508 ms; SD = 124 ms). These two outliers were replaced with two new subjects.

Apparatus and Stimuli The apparatus and viewing distance was the same as that used in Experiments 1-3. A schematic representation of the stimuli and procedure is shown in Figure 2. The selective attention task was identical in stimuli and procedure to that used in experiments 1-3. The difference between Experiment 4 and Experiments 1-3 was in Task 1.

In Task 1, the target stimulus was a left- or right-pointing arrow presented with the midpoint of its shaft at fixation. The arrow was drawn with lines 0.11° thick, and subtended 1.05° horizontally. The arrow wings subtended 0.48° each in length. The signal dictating the S-R mapping was a green or red circle with a diameter of 0.57°, presented at fixation.

Each 96-trial block consisted of 3 fully-counterbalanced sets of all 32 possible combinations of S-R mapping congruency (2), arrow direction (2), flanker compatibility (2), target identity (2), and distractor position (2). Target position (6) was counterbalanced with respect to all to the other factors and the combinations over each pair of consecutive blocks.

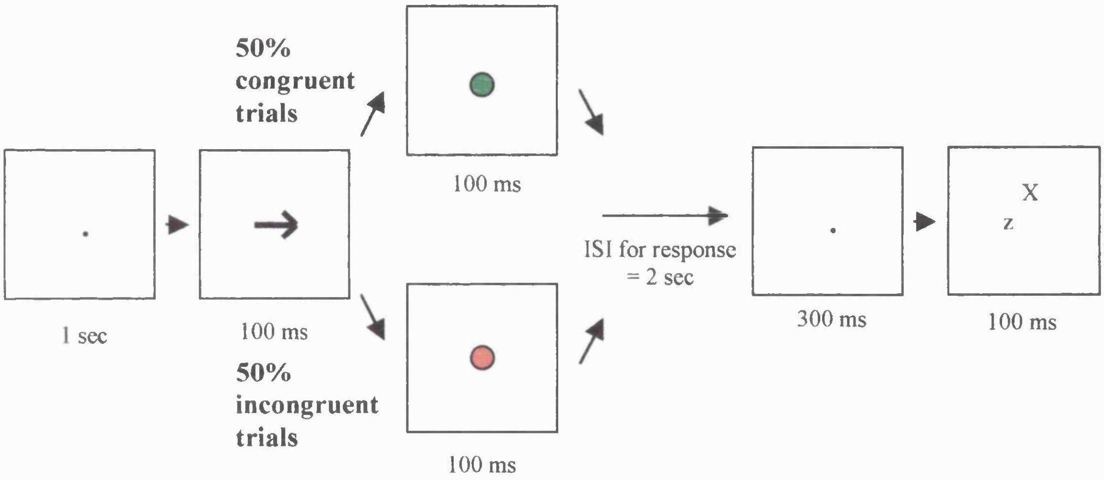


Figure 2. Stimulus sequence and presentation times in Experiment 4

Procedure As in the previous experiments, each trial began with the presentation of a 1-second fixation dot in the centre of the screen for 1 sec. A left-pointing or a right-pointing arrow was then presented at fixation for 400 ms, followed by a red or green signal, displayed for 100 ms. The signal indicated the S-R mapping of responses to the arrow. A green signal indicated a congruent mapping (i.e. respond with left finger for a left-pointing arrow and with right finger for a right-pointing arrow), and a red signal indicated an incongruent mapping (e.g. respond with left finger for a right-pointing arrow, and with right finger for left-pointing arrow). Subjects used the ‘s’ and ‘d’ keys on the computer keyboard with their left hand using the middle and index fingers for ‘left finger’ and ‘right finger’ respectively. Subjects were instructed to make these responses as rapidly as possible, while not sacrificing accuracy, and were given 2 seconds for this response. As before, this time-window elapsed whether or not a response was made.

The flanker task display was then presented preceded by a 300-ms fixation point as in Experiments 1-3. The procedure for the flanker task was the same as that in Experiments 1-3. A 100-ms tone was given as feedback at the end of the trial if a response was missed or an incorrect response made on either task (thus if an incorrect response was made on both tasks, two tones were presented). The congruent and incongruent spatial mappings, as well as the two arrow directions, were intermixed at random within blocks. Each subject performed 6 experimental blocks, initiating each one by pressing the space bar. A practice block of 24 trials, the results from which were excluded from the analysis, preceded the experimental blocks.

Results

Spatial mapping task Individual mean RTs ranged from 365 ms to 690 ms. In the incongruent-mapping trials the group mean RT was 503 ms and the mean error rate was 3.6%, while in the congruent-mapping trials the group mean RT was 462 ms and the mean error rate was 3.9%. The difference in RTs was significant, $t(11) = 2.88$, $p < .025$, consistent with previous findings of longer RTs when spatially incongruent (vs. congruent) responses are made (e.g. Dutta & Proctor, 1992; Wang & Proctor, 1996). There was no significant difference between erreor rates in the two trial types, t(11) < 1.

Table 4 Mean Flanker Task Reaction Times (in ms, standard errors in parentheses) and Error Rate (%) Across Subjects (n=12) as a Function of Distractor Compatibility and Trial Type in Experiment 4

Spatial	Distractor condition				Effect size	
S-R Mapping	*I*		*C*		*I-C*	
In Task 1	RT	%E	RT	%E	RT	%E
IM	785 (57)	13	700 (47)	5	85 (17)	8
CM	716 (47)	10	681 (45)	6	35 (6)	4

Note: I = Incompatible; C = Compatible; IM = Incongruent mapping, CM = Congruent mapping.

Flanker task. Table 4 presents the mean RTs and error rates on the flanker task as a function of the experimental variables. Trials with errors on either the spatial mapping task or flanker task were excluded from the RT analysis. For the RTs, a 2 x 2 repeated measures ANOVA of flanker compatibility and S-R mapping congruency was conducted. As in previous experiments, a main effect of flanker compatibility was obtained: RTs were longer in incompatible trials than in compatible trials, F(1,11) = 32.60, p < .001, indicating a failure to ignore the distractors, consistent with Lavie's findings in similar situations of low perceptual load (e.g. Lavie, 1995) and with the previous findings in this thesis. There was also a main effect of S-R mapping congruency in Task 1, F(1,11) = 30.52, p < .001: flanker task RTs were longer after an incongruent response than after a congruent response in Task 1.

The main result of interest in this experiment was an interaction between S-R mapping congruency in Task 1 and flanker compatibility, F(1,11) = 14.81, $p < .01$. This interaction indicates that, as predicted, the flanker effect was greater after an incongruent response than after a congruent response in the spatial mapping task. The greater distractor effect (in the incongruent versus congruent mapping condition) cannot be attributed to scaling due to slower RTs in the incongruent condition, as the distractor effect in the incongruent condition remained significantly greater than the distractor effect in the congruent condition even when the effect was calculated as the proportion of the overall RT per individual in each condition. The distractor interference effect was 13% of the mean overall RT in the incongruent mapping condition and 6% of the mean overall RT in the congruent mapping condition, and this difference was significant, t(11) = 3.61, $p < .01$.

A similar ANOVA on the error rates revealed a significant main effect of flanker compatibility, F(1,11) = 6.85, $p < .025$, reflecting a higher error rate in incompatible-flanker trials than in compatible-flanker trials. Although there were more errors in the incongruent vs. congruent condition, this trend was not significant, F(1,11) = 2.34, $p = .154$. Similarly, although there was a trend for increased flanker effects in errors (from 4% in the congruent mapping condition to 8% in the incongruent mapping condition), this trend reached only marginal significance, F(1,11) = 3.75, $p = .079$.

Discussion

In Experiment 4, subjects showed greater distractor effects following an incongruent response in Task 1 than following a congruent response. These results provide further support for the idea that engaging inhibition by requiring suppression of the congruent response in the incongruent mapping condition in Task 1 reduces subjects ability to suppress response tendencies to distractors in a selective attention task. Our use of a congruency manipulation that involved suppression of the automatically activated congruent response on incongruent-mapping trials allowed us to generalise the findings from the stopping tasks used in Chapter 2 across another means of manipulating inhibition.

Importantly, Experiment 4 extends our findings to a task in which inhibition is manipulated between two conditions that both involve an executed response. Recall that in Experiment 3 we demonstrated that the difference between Task 1 trials with and without an executed response did not in itself lead to a modulation of distractor effects. Experiment 4 further confirms that the effects of response inhibition can be found without confounding inhibition with response demands. A modulation of distractor effects between two conditions that either involved inhibition or did not involve inhibition was found despite both conditions involving executed responses in Task 1. The results of Experiment 4, together with those of Experiment 3, allow us to rule out any claims that are based on whether or not a response is executed in Task 1.

Experiment 5

The purpose of Experiments 5 and 6 was to investigate the persistence over time of the effect of inhibition on subsequent selective attention performance. Since a fixed time window of two seconds between Task 1 and Task 2 was used in Experiments 1, 2 and 4, it is evident that the effects of inhibition in Task 1 persist over a response-stimulus interval of up to 2 seconds to modulate selective attention performance in the flanker task. In the present chapter we sought to investigate whether the effect of inhibition in Task 1 on selective attention in a subsequent task would become stronger with shorter intervals between Task 1 and Task 2, and also whether the effect would persist over longer intervals than those previously used.

The time-course of the effects of inhibition has been investigated in studies of negative priming (NP). Early studies by Neill and colleagues produced evidence that NP can be reduced by increasing the RSI between prime response and probe target. For example, Neill & Westberry (1987) and Neill & Valdes, (1992) found that lower levels of NP are produced as the RSI between prime and probe increases from 500 ms to around 1 second. However, as discussed in the general introduction, these effects of RSI on NP are not reliable, and appear to depend to some extent on varying RSIs within subjects. In fact NP is often unaffected by RSI when RSI is manipulated between groups of subjects (Hasher, Stoltzfus, Zacks & Rypma, 1991; Stoltzfus, Hasher, Zacks, Ulivi & Goldstein, 1993; Tipper, Weaver, Cameron, Brehaut & Bastedo, 1991). Thus when different groups of subjects received different fixed RSIs, NP was found to persist over RSIs of 1200 ms (Hasher et al., 1991), 1700 ms (Stolzfus et al. 1993) and 6600 ms (Tipper, Weaver, Cameron, Brehaut & Bastedo, 1991).

Moreover, there are findings of NP which does *not* change as a function of RSI when this is varied *within* subjects, showing that NP can persist unchanged over RSIs of 2500 ms (Hasher, Zacks, Stolzfus, Kane & Connelly, 1996), and 4 seconds (Conway, 1999). Also, there have been failures to replicate a suggestion (from

Neill, Valdes, Terry & Gorfein, 1992) that decreases in NP depend on the ratio between RSIs before and after the prime (Conway, 1999). Together, these studies suggest that a decrease in NP as a function of RSI is not a robust finding.

In the majority of experiments investigating a possible decrease in NP during the RSI, the level of NP has remained significant at the longest observed RSIs. Even in studies such as Neill & Valdes (1992) and Neill et al. (1992), which both showed a decrease in NP as RSIs were increased (e.g. from 500 ms to 1 sec as previously described), the level of NP at the longest RSIs (8 seconds and 4 seconds respectively), although lower than that at the shorter RSIs, was still significant. Together with the findings of Conway (1999) and Tipper, Weaver, Cameron, Brehaut & Bastedo (1991), who found significant NP after RSIs of 4 and 6 seconds respectively, these findings indicate that NP can be reliably detected after an RSI of more than 4 seconds.

Furthermore, DeSchepper & Treisman (1996, Treisman & DeSchepper, 1996) found that NP can persist for days and even weeks. However, these findings are confined to task situations involving novel shape stimuli (requiring same/different matching responses) which had never been processed before by the subjects. As such, it is not clear whether such effects can be found in the common NP identification of localisation tasks with familiar stimuli.

While findings of robust NP effects (in typical NP tasks) after RSIs of several seconds appear to be reliable, the persistence of the NP effect need not imply that the distractor remains inhibited throughout the RSI. Distractor inhibition may alter the internal representation of a stimulus, such that its status as an ignored object becomes part of its representation (Tipper, Weaver, Cameron, Brehaut & Bastedo, 1991). Thus, it may be that the long-lasting NP observed in the above studies represents an after-effect of an inhibitory process, rather than the persistence of active inhibition of responses to distractors.

There is, however, an essential difference between the typical NP task and the task used in the present studies, as in NP tasks the probe trial may require a response to the item which served as the prime distractor (as it may be presented as the probe target), and thus the efficiency of performance should suffer if responses to distractors remain suppressed over a long interval after prime responses are made. Instead, it is more efficient to rapidly recover from inhibition so that fast responses to distractor stimuli can be made when these become probe targets. In the task used in the present studies, however, Task 2 did not involve responses to the stimuli of Task 1, and a response to Task 1's stimuli would thus not need to be made until *after* performance of Task 2. Thus in our studies the cost of sustaining inhibition of responses to Task 1 may be less apparent, and it is possible that responses will remain actively inhibited during performance of Task 2. We examined this in the following experiments.

In Experiments 5 and 6, we varied the RSI between Task 1 and the flanker task. In Experiment 5, we used RSIs of 0, 750 and 1500 ms. The 0 ms interval (i.e. the stimuli for Task 2 were presented directly after the response to Task 1) was thus shorter than in our previous experiments, which employed a fixed time window of 2 seconds, and thus typically involved an interval of over 1 sec between the response to Task 1 and the onset of the Task 2 stimuli. The 1500 ms interval was comparable to Experiment 4, as Task 1 RTs in that experiment averaged around 500 ms in (and thus the RSI was 2 seconds minus approximately 500 ms). The 750 ms interval, the midpoint between the 0 ms and 1500 ms intervals, was used as an intermediate value. An early decline, such as that observed in NP by around 1000 ms (Neill & Westberry, 1987; Neill & Valdes, 1992), should be picked up by these intervals.

Method

Subjects & Apparatus 12 students, aged between 18 and 35, took part in the experiment for £5 payment. All had normal or corrected-to-normal vision. One subject was unusually slow on the spatial task (individual mean RT = 637 ms; group mean = 477 ms; SD = 73 ms) as well as the flanker task (individual mean RT = 1088 ms; group mean = 681 ms; SD = 171 ms), and was replaced with another subject. The apparatus and viewing distance were the same as in all previous experiments.

Stimuli and Procedure The flanker task was identical in stimuli and procedure to that used in experiments 1-4. Experiment 5 differed from Experiment 4 only in the duration of the response-stimulus interval (RSI) between Task 1 and the flanker task: the response to Task 1 was followed immediately by an RSI of variable duration, during which the screen was blank. RSIs of 1500 ms, 750 ms, or 0 ms (no RSI) were used at random and with equal probability. After this RSI, the flanker task was presented. The procedure for the flanker task was the same as that in Experiments 1-4. Each subject performed 6 experimental blocks, initiating each one by pressing the space bar. Each 96-trial block consisted of 3 fully-counterbalanced sets of all 32 possible combinations of S-R mapping congruency (2), arrow direction (2), flanker compatibility (2), target identity (2), and distractor position (2). Target position (6) and RSI duration (3) were counterbalanced with respect to each other and all combinations of the other factors over the 6 experimental blocks. A practice block of 36 trials, the results from which were excluded from the analysis, preceded the experimental blocks.

Results

Spatial S-R mapping task Individual mean RTs ranged from 382 ms to 746 ms. The group mean RTs were 512 ms in the incongruent-mapping trials (mean error rate = 2.2%) and 459 ms in the congruent-mapping trials (mean error rate = 2.7%). This difference in RTs was significant, F(1,11) = 31.87, p < .001. There was no difference between accuracy rates in the two trial types, F(1,11) = 1.22, p = .293.

Flanker task Table 5 presents the mean RTs and error rates on the flanker task as a function of the experimental variables. Trials with errors on either Task 1 or the flanker task were excluded from the RT analysis. For the RTs, a 2 x 2 x 3 repeated measures ANOVA was conducted with RSI duration (0, 750, and 1500 ms) flanker compatibility and S-R mapping congruency as factors. As in all previous experiments, a main effect of flanker compatibility was obtained: RTs were longer in incompatible trials than in compatible trials, F(1,11) = 45.69, p < .001, indicating a failure to ignore the distractors. There was also a main effect of S-R mapping congruency in Task 1, F(1,11) = 28.77, p < .001. Flanker task RTs were longer after an incongruent response than after a congruent response in Task 1. RSI did not produce a main effect in RTs, F < 1, and as in Experiment 4 there was also an interaction between S-R mapping congruency in Task 1 and flanker compatibility, F(1,11) = 14.92, p < .01. Flanker effects were greater after an incongruent response was made in Task 1 than after a congruent response was made, replicating the findings of Experiment 4.

Table 5 Mean Flanker Task Reaction Times (in ms, standard errors in parentheses) and Error Rate (%) Across Subjects (n=12) as a Function of Flanker Compatibility and Trial Type in Experiment 5

	Flanker compatibility				Effect size	
	I		*C*		*I-C*	
Trial type	RT	%E	RT	%E	RT	%E
RSI = 0 ms						
IM	722 (48)	7	634 (32)	5	88 (18)	2
CM	665 (31)	5	619 (30)	3	46 (8)	2
RSI = 750 ms						
IM	720 (46)	8	639 (35)	5	81 (13)	3
CM	658 (38)	6	631 (35)	7	27 (11)	-1
RSI = 1500 ms						
IM	705 (43)	9	641 (37)	4	64 (15)	5
CM	662 (40)	6	646 (39)	5	16 (9)	1

Note: I = Incompatible; C = Compatible; IM = Incongruent mapping, CM = Congruent mapping.

The greater distractor effect after incongruent versus congruent trials cannot be attributed to scaling due to slower RTs in the incongruent mapping condition. This difference remained significant even when the effect was calculated as the proportion of the overall RT per individual in each condition. The distractor interference effect was 13% of the mean overall RT in the incongruent mapping condition and 5% of the mean overall RT in the congruent mapping condition, and this difference was significant, t(11) = 4.20, p < .001.

Although there was a trend for smaller flanker compatibility effects overall (i.e. across conditions of S-R congruency in Task 1) with larger RSIs, the interaction between RSI and flanker compatibility did not reach significance, $F(1,11) = 2.77$, $p = .084$. There was no interaction between RSI duration and S-R mapping congruency, $F = 1.02$. Neither was there a 3-way interaction between RSI, mapping congruency and flanker compatibilty, $F < 1$. Thus, the flanker effect was greater after incongruent vs. congruent responses in Task 1 across all 3 levels of RSI. There was no evidence of changes in the strength of this effect as a function of the RSIs employed.

A similar ANOVA on the error rates revealed a significant main effect of flanker compatibility, $F(1,11) = 7.90$, $p < .05$, indicating that in accord with the RTs there was a higher error rate in incompatible-flanker trials than in compatible-flanker trials. In accordance with the RT results, there was a trend for more flanker-task errors in the incongruent mapping condition than in the congruent mapping condition, however it reached only marginal significance, $F(1,11) = 4.04$, $p = .070$. The main effect of RSI duration was not significant, $F(1,11) = 1.09$, $p = .353$. There was also a marginally significant trend towards an interaction between mapping congruency and flanker compatibility in the error analysis, $F(1,11) = 3.74$, $p = .079$. As in the RTs, compatibility effects in errors tended to be greater following incongruent vs. congruent responses. However, as can be seen in Table 5, this was not characteristic of the 0 ms RSI condition. The interaction between RSI duration and mapping congruency was not significant, $F(1,11) = 1.59$, $p = .226$, and neither was the 3-way interaction, $F(1,11) = 1.07$, $p = .360$.

Discussion

The results from Experiment 5 provide a clear replication of the results of Experiment 4, in that the flanker effect was again greater after incongruent vs. congruent responses in Task 1. The results also show that this effect does not change over an RSI of up to 1500 ms. No significant differences were found overall as a function of RSI in this first experiment, in which RSI was varied over relatively short intervals.

Experiment 6

In Experiment 6 we used RSIs of 750, 3000 and 6000 ms, to examine whether the effects of inhibition on distractor rejection can last over much longer intervals than those used in Experiment 5.

Method

Subjects and Apparatus 12 students, aged between 18 and 35, took part in the experiment for £5 payment. All had normal or corrected-to-normal vision. The apparatus and viewing distance were the same as in all previous experiments.

Stimuli and Procedure Experiment 6 was identical to Experiment 5 except that RSIs of 750, 3000 and 6000 ms were used between Task 1 and the flanker task.

Results

Spatial S-R mapping task Individual mean RTs ranged from 333 ms to 841 ms. The group mean RTs were 589 ms in the incongruent-mapping trials (mean error rate = 3.5%) and 532 ms in the congruent-mapping trials (mean error rate = 2.2%). This difference in RTs was significant, F(1,11) = 8.06, p < .05. There was no difference between accuracy rates in the two trial types, F(1,11) = 2.57, p = .137, as in Experiments 4 and 5.

Table 6 Mean Flanker Task Reaction Times (in ms, standard errors in parentheses) and Error Rate (%) Across Subjects (n=12) as a Function of Flanker Compatibility and Trial Type in Experiment 6

	Flanker compatibility				Effect size	
	I		*C*		*I-C*	
Trial type	RT	%E	RT	%E	RT	%E
RSI = 750 ms						
IM	874 (72)	15	770 (59)	5	104 (22)	10
CM	816 (63)	10	767 (58)	4	49 (23)	6
RSI = 3000 ms						
IM	894 (72)	14	787 (61)	6	107 (23)	8
CM	834 (65)	9	766 (57)	8	68 (19)	1
RSI = 6000 ms						
IM	896 (73)	12	782 (63)	5	114 (27)	7
CM	827 (65)	9	775 (66)	6	52 (19)	3

Note: I = Incompatible; C = Compatible; IM = Incongruent mapping, CM = Congruent mapping.

Flanker task Table 6 presents the mean RTs and error rates on the flanker task as a function of the experimental variables. Trials with errors on either Task 1 or the flanker task were excluded from the RT analysis. For the RTs, a 2 x 2 x 3 repeated measures ANOVA was conducted with RSI duration (750, 3000, and 6000 ms) flanker compatibility and S-R mapping congruency as factors. As in previous experiments, a main effect of flanker compatibility was obtained: RTs were longer in incompatible trials than in compatible trials, F(1,11) = 25.57, p < .001, indicating a failure to ignore the distractors. There was also a main effect of S-R mapping congruency in Task 1, F(1,11) = 27.58, p < .001. As in Experiments 4 and 5, flanker task RTs were longer after an incongruent response than after a congruent response in Task 1. There was no main effect of RSI duration, F(1,11) = 1.54, p = .237.

Importantly, once again there was an interaction between S-R mapping congruency in Task 1 and flanker compatibility, F(1,11) = 9.93, p < .01. Flanker effects were greater after an incongruent response was made in Task 1 than after a congruent response was made, replicating the findings of Experiments 4 and 5. There were no interactions involving RSI, F < 1 in all comparisons. As in Experiment 5, therefore, the flanker effect was greater after incongruent vs. congruent responses in Task 1 across all 3 levels of RSI. There was no evidence of changes in the strength of this effect as a function of the RSIs employed.

The greater distractor effect after incongruent versus congruent trials cannot be attributed to scaling due to slower RTs in the incongruent mapping condition, as this difference remained significant when the effect was calculated as the proportion of the overall RT per individual in each condition. The distractor interference effect was 14% of the mean overall RT in the incongruent mapping condition and 8% of the mean overall RT in the congruent mapping condition, and this difference was significant, t(11) = 3.60, p < .01.

A similar ANOVA on the error rates revealed a significant main effect of flanker compatibility, F(1,11) = 13.15, p < .01. Consistent with the RTs, error rates were higher in incompatible-flanker trials than in compatible-flanker trials. Also consistent with the RTs there was a significant main effect of mapping congruency, showing more flanker-task errors in the incongruent mapping condition than in the congruent mapping condition, F(1,11) = 7.93, $p < .05$. The main effect of RSI duration was not significant, F < 1. Importantly our main RT result was replicated in the errors. There was a significant interaction between mapping congruency and flanker compatibility, indicating that there was a greater error-rate flanker effect after incongruent vs. congruent responses in Task 1, F(1,11) = 11.66, p = .01. Neither the interaction between RSI duration and mapping congruency, or the 3-way interaction, were significant, F < 1 for both.

Discussion

In Experiment 6, the flanker effect was greater after a spatially incongruent response vs. a spatially congruent response in Task 1, as in Experiments 4 and 5, and this effect did not vary as a function of the RSI between Task 1 and the flanker task. The results of Experiment 6, together with the results of Experiment 5, demonstrate that the effect observed in Experiment 4 persists unchanged over an RSI of up to 6 seconds.

In evaluating the implications of the findings from Experiments 5 and 6, an important point of comparison is the time-course of NP. NP has been found by some to persist unchanged over RSIs of 4000 ms (Conway 1999) and 6600 ms (Tipper, Weaver, Cameron, Brehaut & Bastedo, 1991). Other studies have found an initial decrease in NP, but even these studies found that the effect was still significant after 4000 ms (Neill et al., 1992) and 8000 ms (Neill & Valdes, 1992). Overall, these studies indicate that there is at least a component of NP which persists over an RSI of several seconds. Our studies in the present chapter show that the effect of inhibition on distractor rejection in a subsequent task persists over RSIs of the same order of magnitude. What can we draw from this about the kind of mechanism responsible for this effect?

It is possible that inhibition mechanisms remained actively engaged in the suppression of congruent Task-1 responses throughout the RSIs used in these experiments. As mentioned previously, Task 2 in our paradigm (the flanker task) does not involve the same stimuli or responses as Task 1 (the spatial S-R mapping task). Thus, as there is no chance that the specific response that is suppressed in Task 1 (on incongruent trials) will be required in Task 2, there is no immediate need to cease active inhibition of that response. Indeed, if the process of releasing a response from inhibition has a performance cost associated with it, it may in fact be more efficient to maintain active inhibition of that response until the next time that response could be required: specifically, the next occurrence of the spatial S-R mapping task (notice also that each trial began with a 1 second fixation dot, an interval that could potentially be used for such processes of release from inhibition). In the NP literature, the findings of long-lasting NP has been attributed to the *after-effects* (rather than the active continuation) of an inhibitory process. That is, it is possible that inhibition changes the stored representation of the ignored item, such that it is processed differently on its next occurrence (e.g. Tipper, Weaver, Cameron, Brehaut & Bastedo, 1991). In the paradigm in the present thesis, a similar suggestion can be made for the results of Experiments 5 and 6: while it is possible that inhibition mechanisms remain engaged in Task 1 six seconds after a response has been given, it might instead be that a change in the state or settings of a mechanism results from the engagement of inhibition in Task 1.

Beyond this, however, the specific implications from the NP literature are limited. There is a fundamental difference between the effects observed in our paradigm and NP effects, in that our findings do not index the status of a particular representation. The NP effect relies on the re-appearance of a specific inhibited object (or a semantic relative of that object), while in our paradigm items from Task 1 do not feature in Task 2. The NP effect relates to the inhibition of a particular representation in the prime, which is accessed again in the probe. Clearly, in the present studies, the observed interaction between inhibition tasks and the flanker task does not require the same stimuli to appear in both tasks. In our paradigm, rather than a particular representation featuring in both tasks, it is a particular *mechanism* which is involved in both tasks (i.e. a mechanism of active inhibition). For the observed effect of inhibition on subsequent selective attention to occur, it is not important *what* it is inhibited, as long as inhibition mechanisms are engaged. Thus, while long-lasting NP may imply a change in a stored representation (Tipper, Weaver, Cameron, Brehaut & Bastedo, 1991), our findings may instead imply a change in a mechanism or resource.

As to the nature of this potential change in a mechanism, one possibility is that the persistence of the carry over effects may be due to a *residual switch cost*. Each trial of our task required switching from Task 1 (either a stop-signal task or a spatial S-R mapping task) to Task 2 (a flanker task). It is possible that the effect of inhibition in Task 1 on the flanker task in Task 2 reflects a cost associated with re-configuring an inhibition mechanism which is involved in both tasks. When a subject switches between two tasks performed on the same stimuli, there is a performance cost on the first trial after a switch, relative to trials which do not follow a switch (Rogers & Monsell, 1995). When the RSI between the two tasks is increased, allowing time for the subject to prepare for a predictable switch, the switch cost lessens, until it reaches a stable level beyond which further increases in RSI do not lessen it further (Allport, Styles & Hsieh, 1994; Rogers & Monsell, 1995).

This residual switch cost has been shown to persist virtually undiminished in all the experiments in which the between-task interval is manipulated (Rogers & Monsell, 1995; Meiran, 1996; Meiran, Chorev & Sapir, 2000; De Jong, 2000). The longest interval studied is in Meiran et al. (2000), in which the residual switch cost remained significant with an interval of 3032 ms between the cue indicating the task to be performed and the onset of the target. Accounts of residual switch costs vary in that some researchers claim that task-sets cannot be fully reconfigured endogenously (e.g. Rogers & Monsell, 1995), while others claim that subjects are not fully motivated to complete the reconfiguration process on every trial (e.g. De Jong, 2000). However, the different accounts are unequivocal in suggesting that the residual switch cost reflects the failure of the subject to fully reconfigure a task-set prior to the occurrence of the second task (i.e. the task being switched to).

Given that our results suggest that a common inhibitory mechanism is shared between the processes of response inhibition and distractor rejection, and the interaction between these two tasks persists over several seconds, it seems plausible that our effect represents a switch cost in the common inhibitory mechanism. In other words, an inhibitory mechanism which is involved in response inhibition in incongruent trials of Task 1 must reconfigure itself in order to contribute to the rejection of perceived distractors in the flanker task. The failure of the mechanism to reconfigure itself completely results in a decrement in its performance on the second of the two tasks, compared to trials in which the mechanism is not active in Task 1 (go trials in Experiments 1-2 or congruent trials in Experiments 4-7).

In sum, the persistence of the carry-over effects of inhibition on flanker task performance reported in this chapter may not necessarily indicate the continued active engagement of inhibition in Task 1. Rather, the results may reflect a switch cost associated with task-set reconfiguration in an inhibition mechanism that is common to both the spatial S-R mapping task and to distractor rejection in the flanker task.

In discussing the possibility that a switch cost underlies the observed effect of engaging inhibition on selective attention, it is important to note that we are not referring to a generalised cost of switching between the first and second tasks in our paradigm. Such a general cost may well have occurred in our task, but as a switch between two tasks is present on *every* trial, and across both congruency conditions in Task 1, such a cost cannot explain the observed difference in performance of Task 2 between the different congruency conditions of Task 1. Rather, in order to explain the persistence of carry-over effects of inhibition in Task 1 on performance of Task 2, the suggestion is that an additional switch cost occurs when the common inhibition mechanism is involved in both tasks. On incongruent mapping trials, when inhibition of the congruent response is required, a reconfiguration of task-set is required for that mechanism to then subsequently engage in rejecting the distractor in the flanker task. However, on congruent mapping trials, inhibition of responses to Task 1 is not required, and there is therefore no need for task set reconfiguration upon the occurrence of Task 2.

What are the implications of Experiments 5 and 6 for the way in which the general hypothesis of this study is framed? The assumption of limited capacity in the inhibition mechanism involved in selective attention can be seen as unnecessary, as the observed effects may simply entail a difficulty in reconfiguration of the task set of the putative inhibitory mechanism, which thus leads to a reduced ability to reject distractors via active inhibition. We note however that our main hypothesis concerns the role of inhibition in distractor rejection and this hypothesis remains supported by the findings that engaging inhibition in Task 1 impairs distractor rejection in Task 2 even when this follows after a delay of 6 seconds. The above account of these results in terms of task-set reconfiguration merely removes the need to invoke capacity limits in inhibition to explain our results, and does not in any way lessen the implication that inhibition is involved in selective attention.

CHAPTER FOUR

Carry-Over Effects of Performing a Stroop Colour-Word Task on the Efficiency of Selective Attention

Introduction

In the present chapter we used a non-spatial manipulation of congruency in the Stroop colour-word paradigm (Stroop, 1935) as a means of engaging inhibition in Task 1. As described in the general introduction, the Stroop task requires subjects to name the colour of a word while ignoring the word's identity. The word can be either congruent, incongruent or neutral with the colour it is displayed in. As also described in the general introduction, RTs in the Stroop task are typically slower when the word is incongruent with its colour than when it is congruent or neutral. A variant of the common colour-naming Stroop task is the word-reading Stroop task, in which the subject attempts to read the word and ignore its colour. As the literature on the Stroop task shows, responses to words are dominant over responses to colours in the Stroop paradigm, and thus correct performance on incongruent colour-naming trials requires inhibition of the dominant response to the word.

The inhibition in the Stroop colour-word paradigm could be at a different level, or on a different processing path, to that involved in the spatial S-R mapping task used in Chapter 3. Specifically, the process of making spatially incongruent responses in Task 1 may have involved a suppression of systems used in the normal processing of spatial information, systems which would also be used in locating the target in the flanker task. For example, perhaps loading of spatial processing systems resulted in greater difficulty in distinguishing target locations from distractor locations, and thus greater interference from distractors in irrelevant positions. The Stroop colour-word paradigm provides a manipulation of congruency which is not spatial. The colour-word stimuli, presented at fixation, are unlikely to afford any particular directional response. Moreover any spatial information contained in the stimuli would not differ across the two levels of congruency. Thus any effects of congruency in this colour-word Stroop task on distractor processing in the following task cannot be attributed to disruption of spatial processing in Task 1.

Another advantage of employing the Stroop paradigm is that it allows us to distinguish empirically between the effects of inhibition and the effects of congruency. Although we varied the S-R congruency in Task 1 as a means of manipulating inhibition in Chapter 3, we hypothesise that it was the requirement to inhibit a dominant response in incongruent trials, not simply the request to make an incongruent response, that led to reduced suppression of responses to distractors (and thus an increased flanker effect) in those experiments. The word-reading and colour-naming versions of the Stroop task both involve manipulations of congruency between the word and the ink colour, but (as I will discuss below) the extent to which *inhibition* is involved in making incongruent responses should differ between the word reading task and the colour naming task in accordance with the dominance of words over colours: as word reading is dominant over colour naming, in colour naming tasks irrelevant words should produce greater interference effects, and require more suppression, than irrelevant colours in word reading tasks. Thus, by using both these versions of the Stroop task in this chapter, we sought to demonstrate that although the two tasks involve the very same stimuli and response effectors, and more importantly, the same type of congruency between the relevant and irrelevant dimensions, the extent to which they would affect distractor processing in the selective attention task would depend on the degree to which they involved inhibition.

The dominance of responses to words in the Stroop task

The dominance of responses to words over responses to colours is crucial to our investigation because, firstly, it creates the need for inhibition when responding to the non-dominant dimension, and secondly, it entails that the colour-naming task requires strong inhibition, while the word-reading task does not. In this section I describe the evidence available for this claim.

By far the most commonly used version of the Stroop task is that in which the ink colour must be named while the identity of the word must be ignored. However, Stroop's seminal article (Stroop, 1935) also included two experiments in which subjects were instructed to read colour-words while ignoring the colour of the ink. Stroop found no interference from incongruent ink colours on word reading times in one experiment, and in another experiment he found a small and unreliable interference effect from the irrelevant colours on the word reading task (a *reverse Stroop effect*) only after subjects were extensively practised on the colour-naming task. The finding of asymmetrical interference from colours vs. words is a robust feature of the colour-word Stroop paradigm, and has been reproduced in numerous studies (e.g. Duncan-Johnson & Kopell, 1980; 1981; Glaser & Glaser, 1982; Glaser & Düngelhoff, 1984; Dulaney & Rogers, 1994; MacLeod, 1998; Logan & Zbrodoff, 1998). Thus it seems as though typically the colour-naming task requires more inhibition of the irrelevant yet interfering words than the word-reading task requires inhibition of irrelevant colours, as these do not typically cause any interference.

Accounts for the dominance of words in terms of automaticity

The dominance of word reading over colour naming in the Stroop task is not surprising, as the vast literature on reading and extracting word meanings in various tasks has typically shown that words are processed very efficiently indeed. Semantic priming studies in which words are presented for a very brief duration and then masked have shown semantic priming effects from those (undetected) words, indicating that words can be processed to a high level even on the basis of very poor and transitory input (e.g. Marcel, 1983; Forster & Davis, 1984).

In addition, when subjects can easily read prime words but are led to expect that the subsequent target word in a lexical decision task will be unrelated to the prime, semantic priming is still observed at short SOAs, despite the fact that subjects should predict no benefit from it (e.g. Neely, 1977). Furthermore, when primes occur during an attentional blink (Raymond, Shapiro & Arnell, 1992), the immediate interval after a target in a rapid series of stimuli, during which conscious detection of stimuli does not occur (e.g. Vogel, Luck & Shapiro, 1998), semantic priming is still observed (Shapiro, Driver, Ward & Sorenson, 1997). These studies suggest that activation of word meanings is automatic and as such cannot be not prevented by the subjects intentions or lack of awareness.

The results from behavioural studies concur with ERP studies in which the N400 component, thought to be sensitive to semantic priming (e.g. Bentin, 1989), is shown to reduce in amplitude (reflecting priming) even when SOAs are too short for subjects to generate expectancies (e.g. De Groot, 1984), when the prime is very unlikely to be related to the target (e.g. Holcomb, 1988), and when the prime occurs during an attentional blink (Rolke, Heil, Streb & Henninghausen, 2001). In general in the word processing literature, the idea that semantic activation spreads automatically between related words (*automatic spreading activation*, e.g. Collins & Loftus, 1975) and the idea that processing at the word level occurs in parallel with processing at lower levels (i.e. automatically, e.g. McClelland & Rumelhart, 1981) have become well established.

The concept of automaticity must be used carefully when applied to the Stroop task, however. Some researchers have attributed the Stroop effect to word reading being automatic in the strong, all-or-none sense of being obligatory and capacity-free (e.g. Posner & Snyder, 1975). More recent studies, however, suggest that instead of an all-or-none conception of automaticity, a continuum of strength of S-R association is more appropriate, in line with the approach used in connectionist models of Stroop task performance (e.g. Cohen, Dunbar & McClelland, 1990).

Extensive practice has been shown to alter the strength of S-R associations in the Stroop task, and consequently to alter the extent to which responses to words are dominant over responses to colours. For example, Dulaney & Rogers (1994) showed that extensive practice in naming the colour of Stroop words and coloured Xs led to the emergence of a reverse Stroop effect on the word reading task. Similarly, MacLeod & Dunbar (1988) assigned colour names to random polygons, and trained subjects to respond to the shapes using these assigned names. Presenting the shapes in both incongruent and congruent colours, MacLeod & Dunbar found that the initial pattern of interference only from colours on shape naming reversed with practice, until after 20 days of training there was interference only from shapes on colour naming. These studies suggest that in the standard Stroop paradigm, the over-learned nature of the word-reading response (due to schooling etc.) dictates that it requires more inhibition than the colour naming response, which has a weaker association with the stimulus. Importantly for our hypothesis both strong and weak conceptions of the automaticity of word reading agree that in the standard stroop colour naming task word reading is dominant over colour naming.

Accounts for the dominance of words in terms of the speed of processing

There is evidence that word reading, in addition to having a stronger S-R association than colour naming, is also faster than colour naming. Manipulations which slow down the processing of words relative to colours have produced the reverse of the normal pattern of interference, suggesting that the pattern of interference found in the standard Stroop task is due in part to words being processed more rapidly than colours.

Gumenik & Glass (1970) and Dyer & Severance (1972) slowed reading by partially masking the colour-word, and found that colours interfered with word reading more than words interfered with colour naming. Similarly, Dunbar & MacLeod (1984) found equivalent reverse and normal Stroop effects when the colour-word stimuli were presented upside-down and reversed. Interestingly, while these studies show that an extreme deviation from the standard Stroop task (i.e. actually degrading the input of the word) can reverse the asymmetry of interference, other studies suggest that the word is still processed even in such situations. For example, even if the task requires responses to letters, not words, as when only a single letter in the word is coloured, the interference from words is greatly reduced (Besner, Stolz & Boutillier, 1997), but negative priming from the word shows that it was nonetheless processed (Marí-Beffa, Estévez & Danziger, 2000). If word reading is faster than colour naming in the standard Stroop task, as these studies suggest, then on incongruent colour-naming trials the word response will reach response production mechanisms before the colour response, and must be inhibited while the colour response reaches completion. On incongruent word-reading trials, however, the incorrect response (to the colour) will reach response production mechanisms only after the correct response (to the word), and thus there is no need for inhibition. This account suggests that in the standard Stroop task, incongruent words require more inhibition than incongruent colours in part because of the greater speed with which they are processed. However it is important to note that speed of processing does not in itself provide an explanation for the Stroop effect, as Glaser & Glaser (1982) and Glaser & Dungelhoff (1984) have shown that the dominance of word over colour cannot be reversed by giving several hundred milliseconds preview of the colour, i.e. giving a head-start to the process of responding to the colour.

Overall, the literature suggests that due to fast and efficient activation of word meanings, as well as the strength of association between words and reading responses, responses to words are dominant over responses to colours in the classic Stroop colour-word task. In turn, the dominance of responses to words suggests that in incongruent colour-naming trials, inhibition of the response to the word is required if performance is to be correct.

Different response modalities in Stroop colour-word tasks

The studies discussed so far converge on the suggestion that in the standard Stroop task, incongruent words require more inhibition than incongruent colours because they are the dominant dimension of the colour-word stimulus. However, the experiments in the present chapter deviate from the standard Stroop task in that a manual key-press response is used instead of a verbal reading/naming response, in order to avoid a switch in response modality between our first (Stroop) and second (flanker) task. It was important therefore to ensure that the dominance of responses to words over responses to colours is not confined to vocal reading and naming tasks, and can be found when manual responses are used. The literature on the Stroop task has established that this is the case.

Manual responses have been used in numerous Stroop studies, and although the congruency effect from words on responses to colours is typically stronger in vocal tasks than in manual tasks (e.g. Logan Zbrodoff & Williamson, 1984; Henik, Ro, Merrill, Rafal & Safadi, 1999), manual tasks have nonetheless consistently produced robust Stroop effects. For example, Keele (1972) required subjects to press keys according to the colours of stimuli which were either colour-words, non colour words, or nonsense letter-like forms. Keele found robust interference from the colour-words, compared to the nonsense stimuli. A notable difference between manual-response studies and vocal-response studies is that reverse Stroop effects (i.e. interference from colours on responses to words) are observed more frequently with manual-response studies. However, the classic asymmetry is still observed, in that these reverse effects are usually smaller than the normal interference effects from words on responses to colours. For example, Logan & Zbrodoff (1998) found significant Stroop effects but non-significant reverse effects with both vocal and typewritten responses to colour words. Pritchatt (1968) required subjects to respond manually to Stroop colour-words using buttons labelled with either word names or colour patches. When responding to the ink colour, a robust Stroop effect was found with both types of label on the keys (see also Besner, Stolz & Boutilier, 1997). When responding to the word, however, a reverse Stroop effect was observed when the buttons were labelled with colour patches, but not when they were labelled with colour names. Sugg & McDonald (1994) required subjects to perform a manual Stroop task using virtual "keys" on a touch-sensitive computer screen. When responding to the colours, the keys were labelled with colour names, and a significant congruency effect was observed. When responding to the words, however, the keys this time labelled with colour patches, the reverse Stroop effect, although significant, was significantly smaller than the congruency effect from the words in the manual colour-naming task. Importantly for the present chapter, these studies demonstrate that the classic asymmetry between interference in word reading and colour naming tasks is still robust in manual Stroop tasks.

Interestingly, the one study that failed to find congruency effects from words to colours also used colour labels on the keys (McClain, 1983). This is likely to be due to the fact that such a task can be performed on the basis of matching the stimulus colour and the colour label on the key. Visually scanning the stimuli, a process which is known to be more conducive to picking out colours than picking out words (Lund, 1927), leads to as much if not more interference from colours to words than from words to colours in matching tasks (e.g. Durgin, 2000; Simon & Baker, 1995; Treisman & Fearnley, 1969).

The manual Stroop task we employed involved no colour labels on the keys. Furthermore, subjects were discouraged from looking at the keys by the use of a viewing hood through which they could see only the display screen, and by the short presentation times used (400 ms). Thus, in our experiment, performing the task on the basis of visual comparison between stimulus and response key was not possible, and a verbal coding of the response keys is likely to have been employed by subjects (i.e. left key = "red"). Such manual Stroop tasks should produce robust interference from words to colours, as the literature reviewed shows. Moreover, the classic asymmetry in the size of interference effects from words to colours is also expected (see Logan & Zbrodoff, 1998; Pritchatt, 1968; Sugg & McDonald, 1994).

Finally, to maximise the likelihood of automatic reading of the words when irrelevant, we employed a very small stimulus set in the Stroop task (red or blue, in red or blue colours). Such small stimulus sets are known to increase priming effects in manual tasks (e.g. Miller 1987). We therefore predicted that in the manual Stroop task we employed, responses to the colour while ignoring the word would involve more inhibition on incongruent trials than would responses to the word while ignoring the colour. Thus the carry over effects on flanker interference in the subsequent flanker task were expected to be greater in the colour naming condition than in the word reading condition.

Experiment 7

In this experiment subjects were asked to make speeded choice responses to a Stroop colour word stimulus in Task 1, and we assessed the effects of congruent vs. incongruent Stroop conditions on a subsequent flanker task. In different conditions of the Stroop task, subjects were required to respond to the colour while ignoring the word, or to respond to the word while ignoring its colour. In the colour-naming task, we expected that in order for subjects to identify correctly the colour of an incongruent stimulus, they would have to inhibit the dominant response, which is to identify the word. We predicted that this demand on inhibition mechanisms would result in the subject being subsequently less able to efficiently draw on inhibition mechanisms for the active rejection of the irrelevant flanker. We thus predicted a greater flanker effect in Task 2 in the incongruent Stroop condition than in the congruent Stroop condition.

In the word-reading task, however, we expected a weaker tendency to respond to the irrelevant colour, and therefore less of a need for inhibition. Thus a smaller effect of congruency in Task 1 on the flanker effect in Task 2 was expected in the word reading condition.

Method

Subjects & Apparatus 12 students, aged between 18 and 35, took part in the experiment for £7.50 payment. All had normal or corrected-to-normal vision. One subject was unusually slow on the flanker task (mean RT of 1117 ms; 2.4 standard deviations from the group mean of 756 ms) and was excluded from the analysis. The apparatus and viewing distance was the same as that used in all previous experiments.

Stimuli and Procedure A schematic representation of the stimuli and procedure is shown in Figure 3. A Stroop colour-word task was used for Task 1. In Task 1, the target stimulus was an upper-case word (equally likely to be "BLUE" or "RED") presented in a red or a blue colour with equal probability, with its midpoint at fixation. Each letter was approximately 0.67° high and 0.38° wide, and was separated from adjacent letters by 0.29° (measured from letter edges). The word "RED" was 1.72° wide and the word "BLUE" was 2.39° wide.

The selective attention task was similar in stimuli and procedure to that used in all previous experiments, with the following exception: the leftmost and rightmost target positions were not used, leaving 4 target positions instead of 6 (so that the potential letter positions covered a similar area to the words in Task 1). Each block contained 96 trials consisting of 3 fully counterbalanced sets of all 32 possible combinations of Stroop congruency (2), colour word (2), flanker compatibility (2), target letter identity (2), and flanker position (2). The target letter was assigned to one of the four positions at random on each trial.

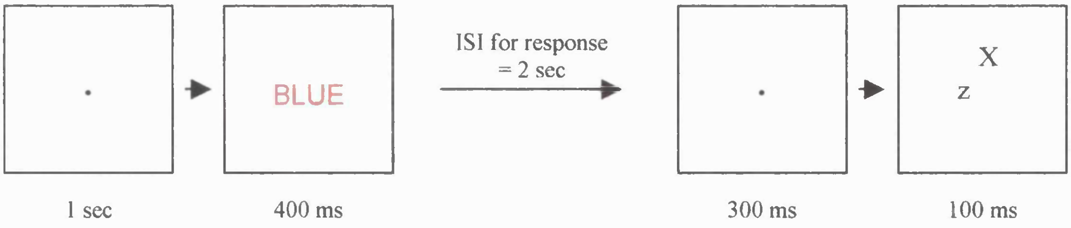


Figure 3. Stimulus sequence and presentation times in Experiment 7. The word and colour dimensions of the Stroop colour-word stimulus could be either congruent or incongruent with each other.

As in the previous experiments each trial began with the presentation of a fixation dot in the centre of the screen for 1 sec. This was followed by the Stroop task, in which a colour-word appeared at fixation for 400 ms. Subjects were required to respond to either the identity of the word or the colour of the word, dependent on an instruction at the start of the block. Subjects pressed the 's' key on the computer keyboard for 'red' and the 'd' key for 'blue' with their left middle and index fingers respectively. Subjects were instructed to make these responses as rapidly as possible, while not sacrificing accuracy. Subjects had 2 seconds in which to make their Stroop task response. This time-window elapsed whether or not a response was made, and was followed by a second fixation dot, presented for 300 ms. The flanker task display then appeared. The procedure for the flanker task was identical to that in all previous experiments. Error feedback for the Stroop task was given at the end of the trial via the presentation of the message "Remember: Word" in the word-reading blocks and "Remember: Ink" in the colour-naming blocks. This message was presented for 2 seconds. Each subject performed practice trials until they had responded correctly on 4 consecutive trials of each level of Stroop congruency and 4 consecutive trials of each level of flanker compatibility. The results from these practice trials were excluded from the analysis. Each subject performed 6 experimental blocks of 96 trials.

Results

Task 1 Table 7a presents the mean RTs and error rates in the Stroop task as a function of the experimental variables. Trials with errors were excluded from the RT analysis. A 2 x 2 repeated measures ANOVA was conducted on the RTs, revealing a main effect of Task-1 type (colour vs. word), F(1,11) = 16.21, p < .01. RTs were longer in the colour task than in the word task. This result is in accordance with previous results showing faster responses to words vs. colours, and provides support for our expectation that word-reading would be dominant over colour-naming in our study.

Table 7a Mean Stroop Task Reaction Times (in ms, standard errors in parentheses) and Error Rate (%) Across Subjects (n=12) as a Function of Relevant Dimension and Stroop Congruency in Experiment 7

Relevant Dimension	Stroop Congruency *I* RT	*I* %E	*C* RT	*C* %E	Effect size *I-C* RT	*I-C* %E
Colour	878 (32)	7	735 (25)	3	143 (13)	4
Word	763 (24)	5	719 (23)	3	44 (15)	2

Note: I = Incongruent; C = Congruent

There was also a main effect of congruency, F(1,11) = 86.70, p < .001. However, this effect was qualified by an interaction between Task-1 type and congruency, F(1,11) = 26.76, p < .001. This interaction indicated that congruency effects were greater in the colour task than in the word task, as predicted. It should be noted, however, that planned comparisons revealed that a significant congruency effect (i.e. longer RTs in incongruent vs. congruent trials) in both the word task, t(11) = 2.967, p < .05, and in the colour task, t(11) = 10.981, p < .001. These findings are consistent with previous Stroop studies involving manual responses, which found greater Stroop effects than reverse Stroop effects (e.g. Logan & Zbrodoff, 1998; Pritchatt, 1968; Sugg & McDonald, 1994). Thus although both the word and the colour were processed even when irrelevant in our task (as indicated by the significant congruency effects they both produced), the congruency effects were over 3 times larger when the word was irrelevant (in the colour task) than when the colour was irrelevant (in the word task), see Table 7a. This seems to indicate that responses to words were dominant over responses to colour and thus required a greater degree of suppression. Thus we expected to find greater effects of congruency on the efficiency of distractor rejection in the flanker task when subjects performed the colour task than when they performed the word task in Task 1.

A similar ANOVA on the error rates revealed that accuracy was greater in the word-reading task than in the colour-naming task, F(1,11) = 5.63, p < .05, in line with the finding of faster RTs in the word-reading task. Also in accordance with the RTs was the effect of congruency F(1,11) = 51.57, p < .001 in the error rates, which was qualified by an interaction between Task-1 type and congruency F(1,11) = 6.64, p < .05. This interaction indicated that congruency effects were greater in the colour task than in the word task, confirming again that responses to words were dominant over responses to colours in this study.

Table 7b Mean Flanker Task Reaction Times (in ms, standard errors in parentheses) and Error Rate (%) Across Subjects (n=12) as a Function of Flanker Compatibility and Trial Type in Experiment 7

	Flanker compatibility				Effect size	
	I		*C*		*I-C*	
Trial type	RT	%E	RT	%E	RT	%E
Colour						
Incongruent	782 (35)	9	670 (31)	5	112 (16)	4
Congruent	726 (30)	11	660 (30)	6	66 (16)	5
Word						
Incongruent	759 (34)	10	678 (39)	5	81 (17)	5
Congruent	755 (31)	9	671 (32)	5	84 (17)	4

Note: I = Incompatible; C = Compatible.

Flanker task Table 7b presents the mean RTs and error rates in the flanker task as a function of the experimental variables. Trials with errors in either the Stroop task or flanker task were excluded from the RT analysis. A 2 x 2 x 2 repeated measures ANOVA was conducted on the RTs with flanker compatibility, Stroop congruency, and Task-1 type as factors. The ANOVA revealed a main effect of Stroop congruency, F(1,11) = 6.73, $p < .025$, reflecting longer flanker-task RTs after incongruent Stroop trials than after congruent Stroop trials. A significant interaction between Task-1 type and Stroop congruency, F(1,11) = 5.39, $p < .05$, indicated that there was a stronger congruency effect on flanker-task RTs in the colour-naming task than in the word-reading task. This was not surprising given that the congruency effect was stronger in the colour-naming task than the word-reading task.

Although the interaction between Stroop congruency and flanker compatibility was not significant, F(1,11) = 3.41, p = .092, there was a significant 3-way interaction of flanker compatibility, Stroop congruency, and Task-1 type F(1,11) = 9.74, $p < .01$. Simple effects analyses revealed that as predicted, the flanker effect in the colour-naming task was greater after an incongruent Task-1 response than after a congruent Task-1 response, F(1,11) = 8.69, $p < .025$, while in the word-reading task, the flanker effect did not differ as a function of Task-1 congruency, $F < 1$.

In the colour-naming condition, the greater distractor effect after incongruent versus congruent trials cannot be attributed to scaling due to slower RTs after incongruent trials, as this difference remained significant when the effect was calculated as the proportion of the overall RT per individual in each condition. The distractor interference effect was 18% of the mean overall RT after incongruent trials and 11% of the mean overall RT after congruent trials, and this difference was significant, t(11) = 2.7, $p < .05$.

There was no interaction between Task 1 type and flanker compatibility, $F < 1$. The average flanker compatibility effects following performance of the colour task and the word task were similar (89 ms and 83 ms in the colour and word tasks respectively). Thus, the general effect of performing a Stroop task prior to a selective attention task was not sensitive to the type of Stroop task (word or colour) or to the size of congruency effects.

A similar ANOVA on the error rates revealed only a significant main effect of flanker compatibility ($F(1,11) = 24.86$, $p < .001$): error rates were 4.3% higher in incompatible-flanker trials than in compatible-flanker trials. There were no other effects in the error rates ($p > .10$ for all other comparisons). Thus, while a flanker effect was clearly observed in the overall error rates, Stroop congruency had no effect on flanker task accuracy.

Discussion

We obtained a significant congruency effect in both the colour-naming and word-reading tasks, yet as predicted the Stroop effect in the colour-naming task was considerably greater than the reverse-Stroop effect in the word-reading task (143 ms vs. 44 ms). This is consistent with previous findings of larger effects from irrelevant words on colour naming than effects from irrelevant colours on word reading in Stroop tasks with manual responses (e.g. Logan & Zbrodoff, 1998; Pritchatt, 1968; Sugg & McDonald, 1994). This finding confirms that word-reading is dominant over colour-naming in our task despite the use of manual responses.

The results of Experiment 7 clearly showed greater distractor effects after an incongruent Stroop display than after a congruent Stroop display in the colour naming condition. This result supports our hypothesis that inhibition of a dominant response results in less efficient selective attention in a subsequent task, and generalises the findings of Chapter 3 to a task in which no disruption of spatial processing is likely to have been involved in the comparison of incongruent and congruent Stroop conditions. Thus, disruption of spatial processing is not crucial for the effect of congruency on distractor processing. Rather, what seems to matter is that subjects have to inhibit a dominant response while making an incongruent response.

We note that the congruency effect in the word-reading task was of the same magnitude as the spatial S-R congruency effect in Experiment 4 (41 ms). Thus it is unlikely that the congruency effect in the word reading condition was simply too weak to have any effect on flanker interference in the flanker task. Instead, our findings suggest that it was the suppression of a dominant response in the colour-naming condition, rather than the presence of congruency per se, that led to the modulation of the flanker effect in the subsequent flanker task.

Experiment 8

In this experiment we addressed a potential alternative account for the results of Experiment 7 in terms of the effects of the difficulty of Task 1. In the Stroop task of Experiment 7, RTs were slowed down by 143 ms in incongruent vs. congruent trials. Although this slowing is presumably due to the processes involved in resolving the conflict in the incongruent condition, the slowing of RTs clearly indicates that the incongruent condition was generally more difficult than the congruent condition. Moreover, overall RTs in the flanker task were also slower after incongruent vs. congruent responses in the Stroop colour task. Thus, although a simple account in terms of scaling of flanker effects in the conditions with slower flanker task RTs is ruled out by our proportional analysis, it is possible that the results of Experiment 7 were due to a more general effect of increased Task 1 difficulty, rather than specifically to the inhibition of dominant responses as we claim. Difficult tasks may, for example, be more demanding on cognitive control mechanisms, and thus may lead to a reduced ability to perform the subsequent flanker task according to current priorities and thus avoid responding to the irrelevant distractors (see Lavie, 2000; Lavie, Hirst, De Fockert & Colledge, submitted). We hypothesised however that it is the increased demand on inhibition specifically (during performance of incongruent trials) that reduced the efficiency of selective attention in the flanker task.

Thus the purpose of Experiment 8 was to investigate whether a manipulation of Task-1 difficulty that should not involve any effect on the availability of inhibition would produce any changes in the flanker effect. In this experiment subjects were required to identify a colour-word written in a neutral colour, and we manipulated the difficulty of perceptual processing in the task by presenting a pattern mask over the word on some trials. The words were "pink" and "blue" instead of "red" and "blue", so that they could not be distinguished from each other on the basis of length when masked. Thus, reading masked words and reading non-masked words constituted the difficult and easy word reading conditions, respectively, in this experiment. By identifying the word, subjects always responded to the dominant dimension of the stimulus. The fact that subjects were never required to respond to the colour, in addition to the fact that the irrelevant stimulus colour was both neutral and invariant, entails that the colour of the stimulus should not have generated response tendencies and thus should not have required inhibition.

If our finding in Experiment 7 of a greater flanker effect in conditions of increased inhibition in Task-1 was due to the increased difficulty of Task-1, then the present experiment should produce a greater flanker effect when the words are masked than when they are not. We hypothesise however that Task-1 difficulty was not the factor which determined the extent of the flanker effect, and thus there should be no difference in the flanker effect between the 'masked' and 'unmasked' conditions.

Method

Subjects & Apparatus 12 students, aged between 18 and 35, took part in the experiment for £5 payment. All had normal or corrected-to-normal vision. One subject was unusually slow on the flanker task (individual mean RT = 1114 ms; group mean = 745 ms; SD = 189 ms). This subject was excluded from the analysis and replaced with a new subject. The apparatus and viewing distance was the same as that used in all previous experiments.

Stimuli & Procedure A schematic representation of the stimuli and procedure is shown in Figure 4. The selective attention task was identical in stimuli and procedure to that used in Experiment 7. A word-reading task was used as Task 1, which differed from the word-reading task of Experiment 7 in the following respects: The words were now presented in a light grey colour, and were "PINK" and "BLUE" instead of "RED" and "BLUE". In the 'masked' condition the word was presented with a row of twenty upper-case "X"s superimposed on it. The "X"s were of the same dimensions as the letters in the target word, and overlapped densely such that the entire row of "X"s subtended 4.67° horizontally. The word was equally likely to be "BLUE" or "PINK", and was equally likely to be masked or not masked.

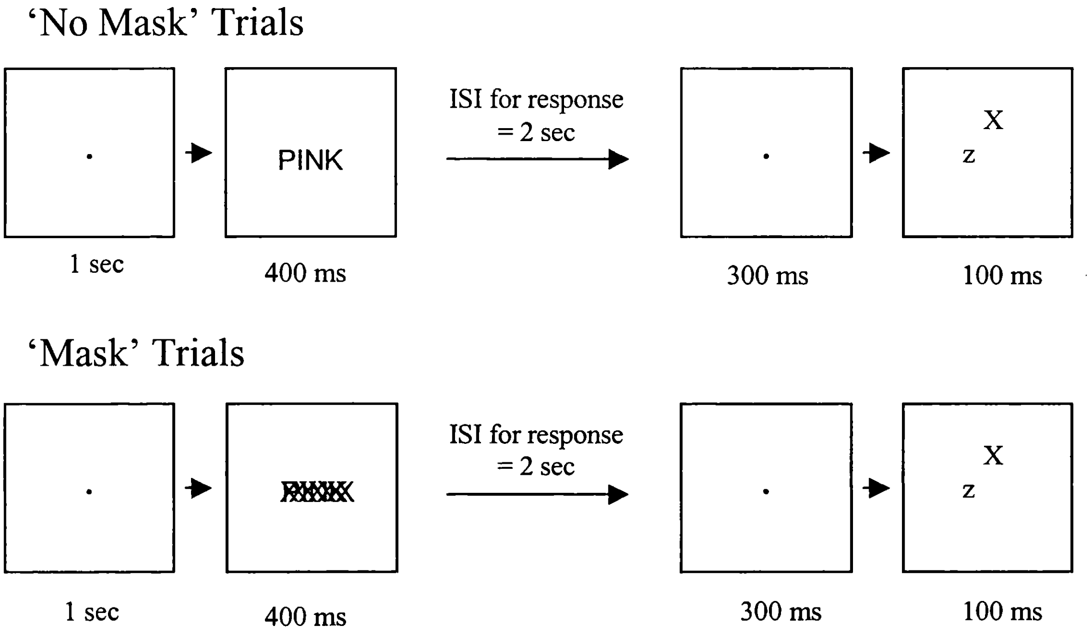


Figure 4. Stimulus sequence and presentation times in Experiment 8. Note that, as in all figures in this thesis, the diagrams are representative of the stimuli, but not exact reproductions. For precise stimulus characteristics see method sections.

Subjects pressed the 's' key for "pink" and the 'd' key for "blue". The procedure for the flanker task was identical to that in Experiment 7. Error feedback in the form of a verbal message on the computer screen ("incorrect response") was given at the end of the trial for 2 seconds. Each subject performed 4 experimental blocks of 64 trials, initiating each one by pressing the space bar. Each block consisted of 2 fully counterbalanced sets of all 32 possible combinations of Task-1 difficulty (2), colour word (2), flanker compatibility (2), target identity (2), and flanker position (2), all randomly intermixed. Target position (4) was counterbalanced with respect to all the other factors and the combinations over each pair of consecutive blocks. Before the experimental blocks, each subject performed 12 practice trials, the results of which were excluded from the analysis.

Results

Task 1 Individual mean RTs in this task ranged from 695 ms to 1367 ms. Trials with errors were excluded from the RT analysis. RTs in the masked condition (M = 1112) were slower by 237 ms than RTs in the unmasked condition (M = 875). This difference was highly significant, t(11) = 5.91, p < .001. Error rates in the masked condition (M = 32%) were 28% higher on average than in the unmasked condition (M = 4%). This difference was also highly significant, t(11) = 7.58, p < .001. These data show a clear difficulty effect that is greater in magnitude than the effect of congruency on RTs (M = 143 ms) and errors (M = 4.5%) in the colour-naming task in Experiment 7.

Table 8 Mean Flanker Task Reaction Times (in ms, standard errors in parentheses) and Error Rate (%) Across Subjects (n=12) as a Function of Flanker Compatibility and Trial Type in Experiment 8

	Flanker Compatibility				Effect size	
	I		*C*		*I-C*	
Task-1 Difficulty	RT	%E	RT	%E	RT	%E
High	867 (58)	8	790 (54)	3	77 (19)	5
Low	882 (55)	8	796 (49)	5	86 (16)	3

Note: I = Incompatible, C = Compatible.

Flanker task. Table 8 presents the mean RTs and error rates on the flanker task as a function of the experimental variables. Trials with errors on either the Stroop task or flanker task were excluded from the RT analysis. A 2 x 2 repeated-measures ANOVA revealed only a main effect of flanker compatibility, F(1,11) = 25.58, p < .001. There was no main effect of Task-1 difficulty, F < 1, nor was there an interaction, F < 1. A similar ANOVA on the error rates indicated a significant main effect of flanker compatibility, F(1,11) = 10.35, p < .01. The main effect of Task-1 difficulty was not significant, F(1,11) = 2.62, p = .13, and neither was the interaction, F(1,11) = 2.41, p = .15. Thus it seems that the flanker effect did not vary significantly as a function of Task-1 difficulty in this experiment. This result contrasts with the results of Experiment 7, where the effect of congruency (and hence of difficulty) in the colour naming task did interact with the flanker effect.

Between-Experiments Comparison

To confirm this contrast between Experiments 7 and 8, a statistical comparison of Experiment 8 and the colour naming condition of Experiment 7 was conducted. For this comparison the incongruent condition of Experiment 7 and the 'masked' condition in Experiment 8 were regarded as 'high difficulty' conditions, and the congruent condition of Experiment 7 and the 'unmasked' condition of Experiment 8 were regarded as 'low difficulty' conditions.

Task 1 2 x 2 mixed-model ANOVAs were performed on the RTs and the error rates, with Task-1 difficulty (high or low) as a within-subjects variable, and experiment as a between-subjects variable. The ANOVAs showed a significant interaction between experiment and Task-1 difficulty in both the RTs, F(1,22) =

5.26, $p < .05$, and the error rates, $F(1,22) = 38.70$, $p < .001$, confirming that there was a greater effect of difficulty in Experiment 8 than in Experiment 7. We can therefore be confident that Task 1 difficulty was manipulated effectively in Experiment 8.

Flanker task A 2 x 2 x 2 mixed-model ANOVA was performed on the RTs, with Task-1 difficulty (high or low) and flanker compatibility as within-subjects variables, and experiment as a between-subjects variable. The 3-way interaction among Task-1 difficulty, experiment and flanker compatibility was significant, $F(1,22) = 7.16$, $p < .025$, showing that the effect of Task 1 difficulty on the flanker effect was significantly greater in Experiment 7 than in Experiment 8. Thus, as predicted, while the manipulation of Task-1 difficulty in Experiment 8 was stronger than that in Experiment 7, the extent to which the flanker effect was influenced by Task 1 difficulty critically depended on the involvement of inhibition in Task 1 (as in Experiment 7, but not Experiment 8).

There was also a significant interaction between Task-1 difficulty and experiment, $F(1,22) =101.72$, $p < .01$, indicating a main effect of difficulty in the flanker task (i.e. slower flanker RTs after incongruent vs. congruent Stroop trials) of Experiment 7, but not in Experiment 8. There was no interaction between flanker compatibility and experiment, $F < 1$.

A similar ANOVA on the error rates revealed no significant interactions, $p > .10$ for all comparisons.

Discussion

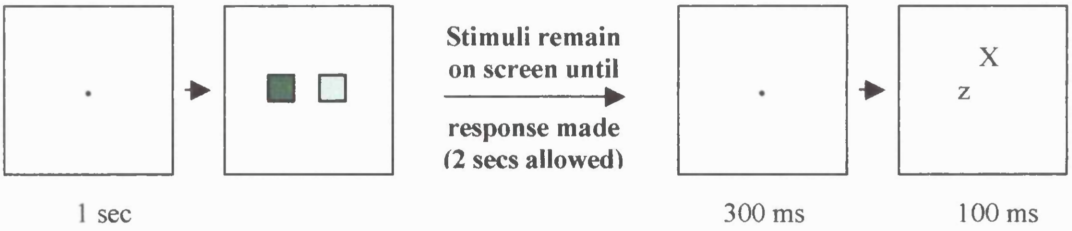
The results of this experiment indicate that an increase in Task-1 difficulty that does not involve inhibition does not have any effect on the extent of distractor interference in the subsequent flanker task. The effect of masking on Task-1 RTs and errors indicates that masking provided an even stronger manipulation of difficulty than the Stroop congruency in Experiment 7, yet in Experiment 7, the flanker effect varied as a function of Stroop congruency. These results help to rule out accounts for the effects of Stroop congruency on distractor interference in a subsequent task in terms of an increase in general task difficulty.

There are two potential problems, however. Firstly, although there was a strong effect of Task 1 difficulty on Task 1 RTs, there was no effect of Task 1 difficulty on overall RTs or error rates in the flanker task. However, in Experiment 7 the general slowing effects of Stroop congruency did lead to a significant slowing of overall RTs in the flanker task. Although scaling of distractor effects with slower RTs after incongruent responses was unlikely to account for our results, as distractor interference was still greater after incongruent vs. congruent response when calculated as a proportion of the overall RTs, it was still desirable to rule out the possibility that only manipulations of task difficulty that have a carry-over effect on the RTs in the following task lead to increased distractor effects. Secondly, the interaction between Stroop congruency and the flanker task was only found in a colour naming task, whereas in Experiment 8 we employed a word reading task as Task 1. To address these issues, in Experiment 9 we manipulated Task 1 difficulty in a task requiring responses to colours.

Experiment 9

In Experiment 9 we attempted to demonstrate that a perceptual manipulation of Task-1 difficulty in a colour discrimination task that does not create a need for inhibition should exert no influence on the flanker effect, even when difficulty effects in Task 1 carry over and have a general slowing effect on RTs in the flanker task. To this end, we chose a colour discrimination task and attempted to manipulate difficulty to a greater extent than that produced by the mask in Experiment 8. In the task we employed here, subjects were asked to discriminate between two colour patches and to identify which of the two patches had the lighter hue. In the difficult discrimination condition the colours were very similar and in the easy discrimination condition the colours were very dissimilar. Clearly, neither of these conditions involved any inhibition. We expected that in Task 1, RTs would be substantially longer in the 'difficult discrimination' condition than in the 'easy discrimination' condition. For the flanker task, we hoped that RTs would be longer

'Easy Discrimination' Blocks



'Difficult Discrimination' Blocks

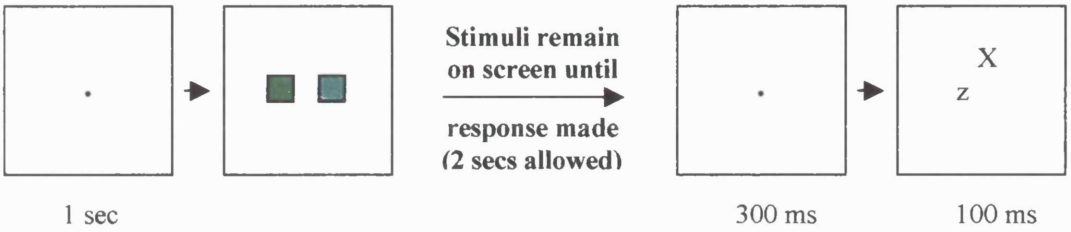


Figure 5. Stimulus sequence and presentation times in Experiment 9

after a difficult discrimination than after an easy discrimination in Task 1, but predicted that no difference in the flanker effect would be observed between these two colour discrimination conditions, as inhibition was not manipulated in the colour discrimination task.

Method

Subjects & Apparatus 20 students, aged between 18 and 35, took part in the experiment for £5 payment. All had normal or corrected-to-normal colour vision. One subject was unusually slow on the flanker task (individual mean RT = 1119 ms; group mean = 740 ms; SD = 140 ms). Another subject performed at chance-level accuracy in the 'difficult discrimination' condition of Task 1 (individual error rate = 51%; group mean = 79%; SD = 7%). These 2 subjects were excluded from the analysis and replaced with 2 new subjects. The apparatus and viewing distance was the same as in all previous experiments.

Stimuli & Procedure A schematic representation of the stimuli and procedure is shown in Figure 5. The selective attention task was identical in stimuli and procedure to that used in Experiment 7. Each trial began with the presentation of a fixation dot in the centre of the screen for 500 ms. In Task 1, two coloured circles of diameter 0.47° were presented with their inner edges 0.58° either side of fixation. The circles were both either red, green, or blue, with equal probability. Each colour was produced using only one of the three phosphor guns in the computer monitor (i.e. only the red gun for red, only the blue gun for blue etc.), with the other guns set at 0. In 'easy discrimination' blocks, the gun was set at 63 (100% intensity) for one circle and 31 (50% intensity) for the other circle. In ‘difficult discrimination’ blocks, the gun was again set at 63 (100% intensity) for one circle but this time at 60 (95% intensity) for the other circle. The lighter circle appeared at random on the left or the right with equal probability. Subjects were required to press the ‘s’ key if the lighter circle appeared on the left, and the ‘d’ key if it appeared on the right, using their left middle and index fingers respectively. The circles remained on the screen until the subject made his or her response, or for a duration of 2 sec if the subject had not responded. Task 1 was followed immediately by a 300 ms fixation dot, signalling the start of the flanker task. The procedure for the flanker task was identical to that in Experiment 7. Error feedback tones for both tasks were given at the end of the trial as in Experiments 1-6.

Each subject performed 4 experimental blocks of 96 trials, 2 ‘easy discrimination’ blocks and 2 ‘difficult discrimination’ blocks, initiating each one by pressing the space bar. Each block consisted of a randomly ordered presentation of 3 fully counterbalanced sets of all 32 possible combinations of colour (2), side (2), flanker compatibility (2), target identity (2), and flanker position (2). Target position (4) was counterbalanced with respect to all to the other factors and the combinations over each pair of consecutive blocks. Before the experimental blocks, each subject performed 24 practice trials, the results of which were excluded from the analysis.

Results

Task 1 Trials with errors were excluded from the RT analysis. RTs in the ‘difficult discrimination’ condition (M = 1084) were slower by 591 ms than RTs in the ‘easy discrimination’ condition (M = 493). This difference was highly significant, F(1,19) = 171.57, p < .001. Error rates in the ‘difficult discrimination’ condition (M = 21%) were 20% higher on average than in the 'easy discrimination' condition (M = 1%). This difference was also highly significant, F(1,19) = 169.93, p < .001. These results therefore show that difficulty in Task 1 was very strongly manipulated.

Table 9 Mean Flanker Task Reaction Times (in ms, standard errors in parentheses) and Error Rate (%) Across Subjects (n=20) as a Function of Flanker Compatibility and Trial Type in Experiment 9

	Flanker Compatibility				Effect size	
	I		*C*		*I-C*	
Task-1 Difficulty	RT	%E	RT	%E	RT	%E
High	782 (36)	6	712 (31)	3	70 (14)	3
Low	745 (38)	6	687 (28)	4	58 (18)	2

Note: I = Incompatible, C = Compatible.

Flanker task Table 9 presents the mean RTs and error rates on the flanker task as a function of the experimental variables. Trials with errors on either the Stroop task or flanker task were excluded from the RT analysis. A 2 x 2 repeated-measures ANOVA was conducted on the RTs. As in all previous experiments, there was a main effect of flanker compatibility, F(1,19) = 16.92, p < .001. Crucially, there was a significant main effect of Task-1 difficulty, F(1,19) = 4.91, p < .05, indicating that flanker task RTs were slower in the 'difficult discrimination' blocks than in the 'easy discrimination' blocks. Thus, as in Experiment 7, flanker task RTs varied as a function of Task 1 difficulty. However, unlike in Experiment 7, the flanker effect itself did not vary with Task 1 difficulty, as illustrated by the lack of an interaction between flanker compatibility and Task 1 difficulty, F(1,19) = 1.38, p = .254. Note that no interaction was present also when the distractor effects were analysed as a proportion of overall RTs in each condition. Proportional distractor effects were 11% in the difficult discrimination blocks and 8% in the easy discrimination blocks, t(19) = 1.38, p = .185.

A similar ANOVA on the error rates indicated a significant main effect of flanker compatibility, F(1,19) = 6.52, p < .05. The main effect of Task-1 difficulty was not significant, F < 1, and neither was the interaction, F < 1.

Between-experiments comparison

As in Experiment 8, the data from Experiment 9 were compared with the data from the colour-naming condition of Experiment 7.

Task 1 2 x 2 mixed-model ANOVAs were performed on the data from Experiment 9 and Experiment 7, with Task-1 difficulty (high or low) as a within-subjects variable, and experiment as a between-subjects variable. There was a significant interaction between experiment and Task-1 difficulty in both the RTs, F(1,30) = 57.37, p < .001, and the error rates, F(1,30) = 56.54, p < .001, indicating that there was a greater effect of difficulty in Experiment 9 than in Experiment 7. Accordingly, if flanker effects do not vary as a function of Task-1 difficulty in Experiment 9, this cannot be attributed to the manipulation of difficulty being too weak.

Flanker task A 2 x 2 x 2 mixed-model ANOVA was performed on the RTs, with Task-1 difficulty (high or low) and flanker compatibility as within-subjects variables, and experiment as a between-subjects variable. The 3-way interaction of Task-1 difficulty, experiment and flanker compatibility was significant, $F(1,30) = 4.16$, $p < .05$, showing that the effect of Task 1 difficulty on the flanker effect in Experiment 7 was greater than that in Experiment 9. Thus, as predicted, only a manipulation of Task 1 difficulty that involved inhibition (via congruency effects) led to a significant modulation of the flanker effect in Task 2. There was no interaction between flanker compatibility and experiment, $F(1,30) = 1.73$, $p = .198$, as the overall size of flanker compatibility effects were similar in the two experiments. There was also no interaction between Task-1 difficulty and experiment, $F < 1$, reflecting a similar slowing of flanker task RTs by Task-1 difficulty in both experiments.

A similar ANOVA on the error rates revealed that flanker-task accuracy was greater in Experiment 7 than in Experiment 9, $F(1,30) = 5.85$, $p < .05$. None of the other interactions were significant, $p > .10$ for all.

Discussion

In Experiment 9 flanker task RTs were slower following a difficult colour discrimination task than following an easy colour discrimination task. Thus, as in Experiment 7, flanker task RTs were slower after the more difficult of the two Task 1 conditions. In Experiment 9, however, the difficult discrimination condition in Task 1 did not produce a greater flanker effect than the easy discrimination condition. Thus, whereas incongruent trials in the colour-naming task of Experiment 7 produced a greater flanker effect than congruent Stroop trials, a similar result was not produced by the difficulty manipulation in Experiment 9. The failure to modulate the flanker effect in Experiment 9 was obtained despite using a manipulation of Task-1 difficulty (colour discrimination) which produced a much stronger effect on overall RTs and accuracy in Task 1 than that produced by Stroop congruency in the colour-naming task in Experiment 7. These results demonstrate that the effect of general task difficulty is not in itself sufficient to alter the efficacy of distractor rejection in the flanker task. Together with the results of Experiment 8, these findings converge on the suggestion that the modulations of the flanker effect observed in Experiments 4 and 7 were due to the engagement of inhibition in Task 1, rather than the difficulty of Task 1.

CHAPTER FIVE

The Role of Perceptual Load in Distractor Inhibition

Introduction

So far in this thesis, we have examined the role of inhibition in distractor rejection under conditions of low perceptual load (the flanker task we used involved just one target, i.e. a relevant set size of one). In this chapter we examine the extent to which distractor rejection via active inhibition processes depends on the level of perceptual load in the flanker task. According to Lavie's perceptual load theory (e.g. Lavie, 1995; Lavie & Tsal, 1994), the level of perceptual load in relevant processing determines the extent to which irrelevant distractors are perceived. In situations of low perceptual load, processing of relevant information does not exhaust perceptual capacity, which "spills over" to the processing of irrelevant information, and the perceived distractors in such situations thus require some active means of selection. However, if a high level of perceptual load in the relevant information exhausts perceptual capacity, the irrelevant distractors are simply not perceived, obviating the need for an active selection process such as inhibition.

Perceptual load theory has received empirical support in studies using various manipulations of load and different measures of distractor processing. For example, Lavie (1995, see also Lavie & Cox, 1997) demonstrated that increasing the number of non-targets presented along with the target in the relevant set led to smaller distractor effects in a flanker task. Reduced effects of distractors were also observed when perceptual load was increased using a discrimination (vs. detection) task, a conjunction (vs. feature) task, and a search for a target among similar (vs. dissimilar) distractors. Furthermore, Rees et al. (1997) demonstrated using fMRI that the neural response to irrelevant motion distractors diminished when subjects performed a high vs. low perceptual load task. These findings strongly suggest that in high perceptual load situations, distractors are not fully perceived, and thus there is no need for an active mechanism to select against them. The purpose of the present chapter was to examine this claim. Specifically, we sought to examine whether the effects of engaging inhibition in Task 1 on subsequent distractor rejection in the flanker task would change as a function of perceptual load in the flanker task. We predicted that whereas carry over effects of inhibition in Task 1 should be found on flanker interference in situations of low perceptual load, there should be no such effects on flanker interference in situations of high perceptual load.

Two previous studies in particular provide a basis for our hypothesis that inhibition is not involved in selective attention in high perceptual load conditions. Maylor & Lavie (1998) manipulated perceptual load in a flanker task performed by young and old adults. Inhibitory ability is thought to suffer age-related impairment (e.g. Hasher & Zacks, 1988), and accordingly the older adults showed greater distractor effects than the younger ones. However, older adults are also thought to have lower perceptual capacity than younger adults (e.g. Ball, Beard, Roenker, Miller & Griggs, 1988), and accordingly small increases in perceptual load brought decreases in distractor effects for the old, but not the young subjects. At a set size of 4 and above, the older adults were no more susceptible to the distractors than the younger adults were. The suggestion that putatively deficient inhibition ceased to be a problem for the older adults as perceptual load increased also implies that inhibition is not relied upon for selection in high perceptual load situations.

Another study testing this issue more directly was conducted by Lavie & Fox (2000). They manipulated perceptual load in the prime trial of a NP paradigm, and found that distractor interference as well as NP is eliminated with higher levels of perceptual load. This finding is consistent with the idea that distractors are not fully perceived under high perceptual load conditions, and that inhibition is therefore not involved in distractor rejection under these conditions. However, this finding runs counter to "pure" inhibition views of selection (e.g. Driver & Tipper, 1989) which hold that inhibition is the means of selection in all situations. In our paradigm, such views would predict that engaging inhibition would lead to less efficient distractor rejection in high as well as low perceptual load situations. In this chapter I present two experiments which test this view against our hypothesis that inhibition is only involved in selection in situations of low perceptual load.

In these experiments we manipulated the availability of inhibition in Task 1 using a S-R mapping task as in Chapter 3 (Experiment 10) or a Stroop colour-word task as in Chapter 4 (Experiment 11). The effects of these manipulations on distractor interference in the flanker task were assessed under low perceptual load (as before) or high perceptual load in the flanker task. A high level of perceptual load was produced by increasing the size of the relevant set of letters in the flanker task to six (i.e. one target and five non-targets), as in Lavie (1995). The low perceptual load condition involved a relevant set size of one (i.e. target letter only), as in Experiments 1-9. In the low perceptual load condition we expected distractor effects to be greater after incongruent S-R mapping trials or incongruent Stroop trials in Task 1, as in Experiments 4 and 7. In the high perceptual load condition, we expected that distractors would be passively rejected through lack of perceptual capacity, and thus the distractor effects should be small and should not vary as a function of the demands on inhibition (manipulated via congruency) in Task 1.

Experiment 10

In Experiment 10 we used a spatial S-R mapping task for Task 1 (as in Chapter 3), while manipulating perceptual load in the flanker task through relevant set size.

Method

Subjects 14 students, aged between 18 and 35, took part in the experiment for £5 payment. None had participated in any of Experiments 1-9. All had normal or corrected-to-normal vision. Two subjects were unusually slow on the flanker task (individual mean RTs of 1052 ms and 1097 ms, both were over 2 SDs from the group mean of 821 ms). These 2 outliers were replaced with 2 new subjects.

Stimuli & Procedure Experiment 10 was similar to Experiment 4 except for the addition of a high perceptual load condition to the flanker task. The high perceptual load display consisted of a row composed of the upper-case non-target letters J, K, R, S, and V, plus a target letter – either X or Z. The target letter and the five non-target letters were all of the same dimensions as as the target letters in Experiments 1-4. They occupied the same six positions on the screen as the six target positions in Experiments 1-4. See Figure 6 for a diagram of the two perceptual load conditions.

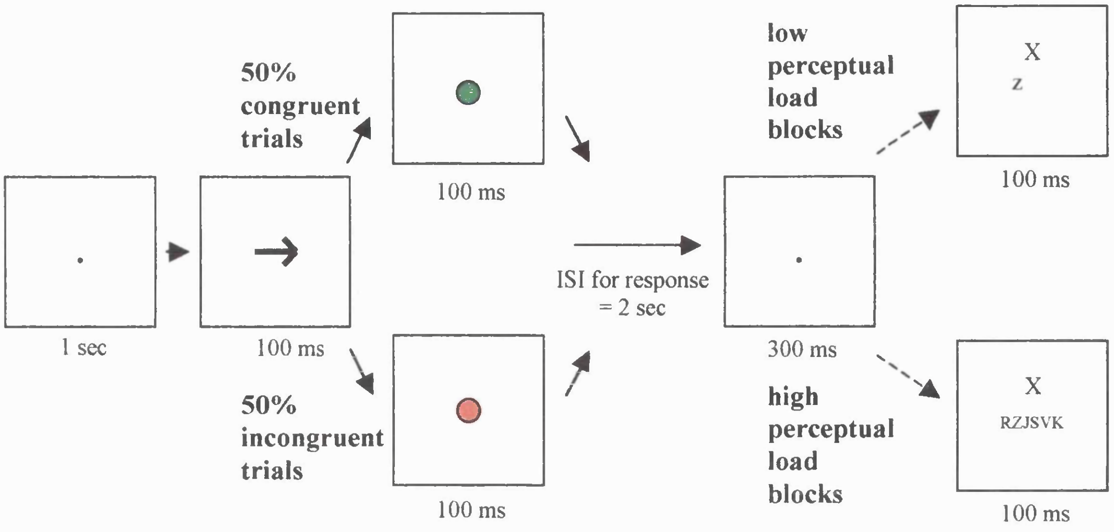


Figure 6. Stimulus sequence and presentation times in Experiment 10

The procedure of Experiment 10 was the same as that of Experiment 4 except for the addition of blocks of trials with high perceptual load. As before, the flanker-task target-letter position was fully counterbalanced with all combinations of the other variables (flanker compatibility (2), target identity (2), distractor position (2), arrow direction (2) and S-R mapping congruency (2)) over each pair of consecutive blocks. The non-target letters in the high perceptual load flanker task were randomly assigned to the five remaining positions on each trial. Subjects alternated between high and low perceptual load blocks, performing 4 blocks of each in total. Half the subjects began with a low load block and the other half began with a high load block. Before the experimental blocks, subjects performed two practice blocks of 24 trials (one for each perceptual load condition), both of which were excluded from the analysis.

Results

Spatial mapping task Individual mean RTs ranged from 343 ms to 623 ms. As in Experiment 4, RTs were significantly longer in incongruent-mapping trials (mean = 522 ms) than in congruent-mapping trials (mean = 489 ms), t(13) = 2.47, p < .05. Thus, spatial S-R congruency was successfully manipulated, as in Experiments 4-6. Error rates were also higher in the congruent-mapping trials (error rate = 2.8%) than in incongruent-mapping trials (error rate = 1.9%), t(13) = 2.12, p = .054.

Table 10 Mean Flanker Task Reaction Times (in ms, standard errors in parentheses) and Error Rate (%) Across Subjects (n=14) as a Function of Distractor Compatibility and Trial Type in Experiment 10

	Distractor compatibility				Effect size	
	I		*C*		*I-C*	
Trial type	RT	%E	RT	%E	RT	%E
Low load						
IM	799 (36)	7	716 (32)	2	83 (18)	5
CM	769 (35)	5	722 (32)	4	47 (16)	1
High load						
IM	891 (23)	13	892 (27)	9	-1 (12)	4
CM	896 (26)	11	883 (28)	10	13 (11)	1

Note. I = Incompatible; C = Compatible; IM = Incongruent Mapping; CM = Congruent Mapping.

Flanker task Table 10 presents the mean RTs and error rates on the flanker task as a function of the experimental variables. Trials with errors on either the spatial mapping task or flanker task were excluded from the RT analysis. A 2 x 2 x 2 repeated measures ANOVA was run on the RTs with the variables perceptual load (high; low), flanker compatibility (compatible; incompatible) and S-R mapping congruency (congruent; incongruent). This analysis revealed a main effect of perceptual load, F(1,13) = 29.18, p < .001, indicating longer RTs in high perceptual load blocks. There was a non-significant trend for longer RTs in incongruent-mapping trials than in congruent-mapping trials, F(1,13) = 3.87, p = .071, in line with the main effect of congruency on flanker task RTs found in Experiment 4. There was also a main effect of flanker compatibility: RTs were longer in incompatible trials than in compatible trials, F(1,13) = 31.59, p < .001. This effect was qualified, however, by an interaction between perceptual load and flanker compatibility, F(1,13) = 9.85, p < .01, which indicated that distractor effects were significantly reduced by high perceptual load as we predicted. Indeed, planned comparisons revealed that in the low perceptual load blocks the compatibility effect was highly significant, F(1,13) = 25.46, p < .001, while in the high perceptual load blocks there were no significant effects of distractor compatibility, F < 1. These results are consistent with previous demonstrations that distractor effects are reduced as a result of increases in perceptual load (e.g. Lavie, 1995).

There was no interaction between S-R mapping congruency and flanker compatibility, F(1,13) = 1.11, p = .321, but there was a significant 3-way interaction, F(1,13) = 6.91, p < .025. This interaction indicated that whereas in low perceptual load blocks the flanker effect was significantly greater in incongruent vs. congruent mapping conditions, F(1,13) = 5.50, p < .05, in high perceptual load blocks there was no significant effect of congruency on the flanker effect, F(1,13) = 1.34, p = .27. Thus, the imposition of high perceptual load significantly reduced the flanker effect (as shown by an interaction between perceptual load and flanker compatibility), resulting in no effect of congruency on distractor processing, as predicted.

A similar ANOVA on the error rates revealed a significant main effect of flanker compatibility, F(1,13) = 17.90, $p < .001$, reflecting a higher error rate in incompatible-flanker trials than in compatible-flanker trials. There was also a main effect of perceptual load, F(1,13) = 19.66, $p < .001$, indicating more errors in high perceptual load blocks. There was no main effect of S-R mapping congruency, $F < 1$. There was a significant interaction between S-R mapping congruency and flanker compatibility, F(1,13) = 7.98, $p < .025$, which indicates a greater error-rate distractor effect in the incongruent-mapping trials. None of the other interactions were significant, $F < 1$ for all.

Discussion

These results demonstrate that high perceptual load reduced distractor effects and that congruency affected distractor processing only under low perceptual load. The finding that the engagement of inhibition lowers the efficiency of distractor rejection in low but not high perceptual load conditions of the flanker task supports the hypothesis that inhibition is required for selection in low but not high perceptual load conditions. This result is consistent with the finding of Lavie & Fox (2000) that NP is also reduced by high perceptual load. The argument that inhibition is always a mechanism of selection (e.g. Driver & Tipper, 1989) is therefore not supported by this result.

Experiment 11

In order to corroborate the results of Experiment 10, in Experiment 11 we examined the effects of perceptual load on the extent to which carry over effects on distractor rejection are found from a congruency manipulation in a Stroop colour naming task. As in Experiment 10, we predicted that in the low perceptual load condition we would observe a greater flanker effect after incongruent vs. congruent responses were made in Task 1. In the high perceptual load condition, we expected that distractors would simply not be perceived and thus the extent to which inhibition is engaged in the incongruent vs. congruent conditions of Task 1 would have no impact on the flanker effect: no effect was expected in the high load task across both Task-1 congruency conditions.

Method

Subjects 16 students, aged between 18 and 35, took part in the experiment for £5 payment. All subjects were native English speakers, and none had participated in any of our previous experiments. All had normal or corrected-to-normal vision, and normal colour vision. One subject was unusually slow on the Stroop task (individual mean RT = 1277 ms; group mean = 919 ms; SD = 180 ms). Another subject was unusually inaccurate on the high perceptual load flanker task (individual mean error rate = 31%; group mean = 13%; SD = 8%). These 2 outliers were replaced with 2 new subjects.

Stimuli & Procedure The Stroop task (Task 1) in Experiment 11 was the same as the colour-naming Stroop task in Experiment 7. The flanker task in Experiment 11 was the same as the flanker task used in Experiment 10. Before each experimental block of the colour-naming and flanker tasks, a short block of 12 trials of a word-reading task was performed. This task was included in order to bolster the association between the word dimension of the Stroop stimuli and a response to that word, in order to ensure the dominance of the word response over the colour response (and the resultant need to inhibit the incongruent word).

The flanker-task target-letter position was fully counterbalanced with all combinations of the other variables (flanker compatibility (2), target identity (2), distractor position (2), colour word (2) and Stroop congruency (2)) over each pair of consecutive blocks. The non-target letters in the high perceptual load flanker task were randomly assigned to the five remaining positions on each trial, as in Experiment 10. Subjects alternated between high and low perceptual load blocks, performing 4 blocks of each in total. They began with a practice block of 24 trials for each perceptual load condition, both of which were excluded from the analysis.

Results

Stroop task The 12-trial word-reading blocks were included purely as training, and the results from these blocks were not analysed. In the colour-naming blocks, individual mean RTs ranged from 579 ms to 1178 ms. As in Experiment 7, RTs were significantly longer in incongruent ($\underline{M}$ = 943 ms) trials than in congruent trials ($\underline{M}$ = 841 ms), $F(1,15) = 42.79$, $p < .001$. Also, there were significantly more errors in incongruent trials ($\underline{M}$ = 4.6%) than in congruent trials ($\underline{M}$ = 2.0%), $F(1,15) = 31.56$, $p < .001$. Thus, Stroop congruency was again appropriately manipulated.

Flanker task Table 11 presents the mean RTs and error rates on the flanker task as a function of the experimental variables. Trials with errors on either the Stroop task or flanker task were excluded from the RT analysis. A 2 x 2 x 2 repeated measures ANOVA was run on the RTs with the variables perceptual load (high; low), flanker compatibility (compatible; incompatible) and Stroop congruency (congruent; incongruent). This analysis revealed a main effect of perceptual load, F(1,15) = 29.90, < .001, indicating longer RTs in high perceptual load blocks, and confirming that perceptual load was successfully manipulated. As in Experiment 7, there was a main effect of Stroop congruency, reflecting longer RTs after incongruent Stroop trials than after congruent Stroop trials, F(1,15) = 10.60, p < .01. There was also a main effect of flanker compatibility: RTs were longer in incompatible trials than in compatible trials, F(1,15) = 74.09, p < .001, however as in Experiment 10, the effect of flanker compatibility was qualified by a significant interaction between perceptual load and flanker compatibility, F(1,15) = 16.50, p < .001. This interaction indicated that distractor effects were again significantly reduced by high perceptual load, consistent with Experiment 10 and Lavie's (1995) previous findings. Distractor effects were 99 ms on average in low load, F(1,15) = 49.17, p < .001, and the trend for a flanker compatibility effect in high load (M = 17 ms) was not significant, F(1,15) = 2.94, p = .107. There was no interaction between Stroop congruency and flanker compatibility, F < 1, however a significant 3-way interaction, F(1,15) = 9.85, p < .01, revealed that flanker effects were greater after incongruent vs. congruent Stroop displays only in the low perceptual load condition, as confirmed by a planned comparison in low load, F(1,15) = 6.82, p < .025. There was no such interaction between flanker compatibility and Stroop congruency in the high perceptual load condition, F(1,15) = 1.28, p = .275.

A similar 2 x 2 x 2 ANOVA on the error rates revealed a significant main effect of flanker compatibility, F(1,15) = 7.26, p < .025, with a greater error rate in incompatible-flanker trials than in compatible-flanker trials. There was also a main effect of perceptual load, F(1,15) = 12.02, p < .01, indicating more errors in high vs. low perceptual load blocks. There were no other significant effects, p > .10 for all.

Table 11 Mean Flanker Task Reaction Times (in ms, standard errors in parentheses) and Error Rate (%) Across Subjects (n=16) as a Function of Distractor Compatibility and Trial Type in Experiment 11

	Distractor compatibility				Effect size	
	I		*C*		*I-C*	
Trial type	RT	%E	RT	%E	RT	%E
Low load						
Incongruent	940 (46)	8	821 (46)	5	119 (16)	3
Congruent	875 (46)	7	796 (44)	6	79 (16)	1
High load						
Incongruent	970 (32)	12	963 (37)	12	7 (10)	0
Congruent	978 (36)	13	951 (32)	10	27 (16)	3

Note. I = Incompatible; C = Compatible.

Discussion

Perceptual load again reduced distractor effects in this experiment, in accordance with Experiment 10 and previous perceptual load experiments (for review see Lavie, 2001). Importantly, whereas in low perceptual load distractor effects were increased in the incongruent vs. congruent Stroop condition, in high perceptual load there was no significant effect of Stroop congruency on distractor processing. Together with Experiment 10 these results provide support for our suggestion that inhibition is only required for distractor rejection in situations of low perceptual load, where distractors are perceived (e.g. Lavie, 1995), while in high perceptual load situations distractors are simply not perceived and thus require no inhibition.

Note that these results do not imply that inhibitory selection mechanisms *cannot* be active in performance of tasks involving high perceptual load. Rather they suggest that inhibition is simply not needed for selection in these conditions because distractors are not processed to an extent that would necessitate their suppression.

CHAPTER SIX

General Discussion

In the introduction to this thesis, I discussed how the nature of selective attention – specifically, whether it operates by active or passive means – depends on the level of perceptual load in the relevant information of a task (Lavie, 1995; Lavie & Tsal, 1994; Rees et al., 1997). Previous work by Lavie and colleagues has demonstrated that a high level of perceptual load which exhausts perceptual processing resources results in irrelevant information being passively excluded from perceptual processing due to insufficient remaining perceptual capacity with which to process it. A low level of perceptual load, on the other hand, does not exhaust perceptual capacity, and previous studies have showed that low perceptual load typically leads to the perception and identification of items that are irrelevant to the task at hand. Thus, an active means of selection is required in low perceptual load situations to prevent these fully perceived yet irrelevant items from leading to unwanted responses. The experiments presented in this thesis provide a new line of behavioural evidence for the suggestion that active inhibition is part of selective attention processes in situations of low perceptual load when irrelevant distractors are perceived.

Summary of findings

Experiment 1 demonstrated that stopping a response in a stop-signal task leads to an increased flanker effect in a subsequent selective attention task. Thus, by engaging inhibition in Task 1, distractor rejection in a subsequent task is made less efficient, suggesting that this distractor rejection process is reliant on an active inhibition process related to that involved in the stop-signal task. Experiment 2 demonstrated that the increased flanker effect in stop trials is not due to the relative frequency of these trials, as it is observed whether stop trials constitute a minority *or* a majority of all trials. Furthermore, Experiment 3 showed that the mere lack of a response in Task 1 does not in itself lead to an increased flanker effect if it does not involve inhibition.

In Experiment 4, it was demonstrated that responding to an arrow stimulus using a spatially incongruent S-R mapping leads to an increased flanker effect compared to responding congruently. As making a spatially incongruent response involves the inhibition of the dominant, congruent, response, this finding generalises the result of Experiment 1 to another response inhibition paradigm, and reinforces the suggestion from Experiment 3 that the response demands of Task 1 (i.e. making vs. not making a response) are not in themselves responsible for the observed differences in the flanker effect.

Experiments 5 and 6 show that engaging inhibition in Task 1 leads to an increased flanker effect even when the flanker task occurs 6 seconds later. These experiments involved 5 different lengths of RSI, and found no evidence that the effect of inhibition on subsequent selective attention changes over time. These results might indicate that inhibition mechanisms remain actively engaged in suppressing the congruent response in Task 1 for at least as long as 6 seconds after the correct response has been made (possibly because a response to the next occurrence of Task 1 is only required after the flanker task, creating no strong incentive to recover from inhibition of responses to Task 1), leaving fewer inhibitory resources available for distractor rejection in the flanker task. Alternatively, it may be that instead of the active persistence of an inhibition process (which might be expected to show some degree of dissipation over time), these results reflect processes of reconfiguration of the task-set of an inhibition mechanism that is common to Task 1 and the flanker task. That is, after an incongruent response in Task 1 the inhibition mechanism, still configured to inhibit a spatially congruent response in Task 1, must re-configure itself to act on the distractor in the flanker task, leading to less efficient distractor rejection.

In Experiment 7, the main result of this series of experiments – that engaging inhibition in one task leads to less efficient distractor rejection in a subsequent flanker task – was generalised to a third response inhibition task: the colour-word Stroop task. The absence of directional information in the colour-word stimuli rules out a disruption of normal spatial processing as an explanation for previous results. Importantly, the finding that the flanker effect was increased after an incongruent (vs. congruent) response in a colour-naming task, but not in a word-reading task, indicates that the presence of incongruency or conflict does not in itself lead to an increased flanker effect, *unless* the resolution of that conflict requires the suppression of a dominant response.

The incongruent condition of the colour-naming task, as well as involving inhibition of dominant responses (to the word), was also simply more difficult than the congruent condition, as evidenced by longer RTs and greater error rates. However, Experiments 8 and 9 show that the difficulty of Task 1, when manipulated by perceptual means and not via the congruency of an irrelevant yet dominant response that requires inhibition, does not by itself lead to modulations of the flanker effect.

Finally, in Experiments 10 and 11 it was demonstrated that the engagement of inhibition (via spatially incongruent responses or incongruent Stroop colour-naming responses) in Task 1 only affects distractor rejection in the flanker task when the flanker task involves a low level of perceptual load in the relevant information. When there was high perceptual load in the flanker task, effects of irrelevant flankers were not increased by the engagement of inhibition in Task 1, and remained at non-significant levels throughout.

Together, the findings presented in this thesis suggest that in situations of low perceptual load, an active mechanism of distractor inhibition is involved in rejection of perceived distractors, while in situations of high perceptual load this mechanism is not involved in selection. The suggestion that an active means of selection is required only in low perceptual load situations is consistent with the hybrid model of selective attention forwarded by Lavie (1995; Lavie & Tsal, 1994).

The findings in this thesis not only support the idea that a passive means of selection occurs in high perceptual load (due to the exhaustion of perceptual capacity in relevant processing) and an active means of selection occurs in low perceptual load (where the unused perceptual resources lead to distractors being perceived), as Lavie's model proposes, but they also provide a clear new line of evidence that active inhibition is part of the active selection process that is required in low perceptual load situations.

This new evidence for the role of inhibition in selective attention converges with active inhibition theories of selective attention (e.g. Houghton & Tipper, 1994;

1996; 1998; Neill 1977; Tipper, 1985; 2001). Moreover, the observed effects of perceptual load on the extent to which inhibition is involved in distractor processing (Chapter 5), agree with the reactive inhibition view that greater initial excitation evokes greater inhibitory feedback (e.g. Houghton et al., 1996), as our findings suggest strong involvement of inhibition in selection in situations where distractor processing is more extensive (i.e. low vs. high perceptual load situations).

Relationship to previous findings of interactions between stop signal tasks and selective attention tasks

The findings in this thesis also converge with previous suggestions that performance on flanker tasks involves inhibition mechanisms such as those engaged by performance of stop-signal tasks. For instance, Kramer et al. (1994) and Ridderinkhof et al. (1999) both demonstrated that when a stop-signal was used to command inhibition of responses to a target in a flanker task, subjects were poorer at stopping responses to incompatible displays than they were at stopping responses to compatible displays. Kramer et al.'s and Ridderinkhof et al.'s results show an interaction between a stop-signal task and a flanker task, and thus concur to some extent with our own findings of an interaction between these two tasks. However, the findings in this thesis provide more direct evidence for the involvement of inhibition in selective attention. Firstly, as discussed in Chapter 1, Kramer et al. and Ridderinkhof et al.'s findings may simply indicate that it is more difficult to stop a response on an incompatible trial because on such trials two responses are activated (one response to the target and the other to the distractor), and on some models it should be harder to inhibit two responses than one (e.g. fan effects models of inhibition: Neumann & DeSchepper, 1992). Secondly, the present research provides an entire series of experiments that are focused on the issue of the involvement of inhibition in selective attention. These experiments show an interaction between inhibition tasks and selective attention tasks that generalises across three different inhibition tasks, and they involve manipulations that rule out numerous alternative explanations for the findings in each experiment paradigm used.

As discussed in Chapter 2, Tipper, Weaver, Cameron, Brehaut & Bastedo (1991) produced a result suggesting that the inhibition involved in go/no-go tasks may be distinct from the inhibition involved in selection (to the extent NP indexes such inhibition). In their study, a go/no-go task was placed in between the prime and probe trials of a NP task, and no difference was found in the level of NP between trials with a go task and trials with a no-go task between prime and probe. Our findings, on the other hand, suggest that the inhibition involved in stopping responses is indeed related to the inhibition involved in selective attention, in conflict with Tipper et al.'s suggestion. As discussed in Chapter 2, Tipper et al. may have failed to find a modulation of NP because of an insufficiently strong manipulation of inhibition. The nogo trials in their go/nogo task involved a stimulus that was never associated with a response, and thus is unlikely to have triggered strong response preparation and the resultant inhibition when a prepared response is witheld. Our findings suggest that a stronger manipulation of inhibition, using a task in which the stimulus on inhibition trials has been associated with a response on other trials, as with the stop signal task in Chapter 2 of this thesis, might have led to a modulation of NP in Tipper et al.'s task. However, we note that a possible problem for interpreting such a result would be that any observed modulation of NP could be due to a change in episodic retrieval, rather than a change in inhibition.

The relationship between Stroop-like tasks and the flanker task

Our use of the colour-word Stroop task in Chapter 4 and the spatial S-R mapping task in Chapter 3 was motivated by the involvement of a clear dominant response which requires suppression on incongruent trials in both these tasks. However, Stroop-like tasks and flanker tasks both involve somewhat similar selection processes (i.e. selection of the relevant target dimension in the Stroop task or selection of the target vs. distractors in the flanker task). This raises the issue of whether the Stroop task and the spatial S-R mapping task interacted with the flanker task in Chapters 3 and 4 simply because they are all selection tasks, with many processes in common, allowing the interaction between them to occur at a level other than inhibition.

Although this is a plausible alternative account for the results of Chapters 3 and 4, the fact that the findings in these chapters converge with the findings from Chapter 2, in which the stop signal task was used to engage inhibition, is supportive of the suggestion that the common process engaged by all three tasks used for Task 1 is inhibition.

Moreover, the finding that the word reading Stroop task in Experiment 7 produced no modulation of the flanker effect strengthens the suggestion that the effects of congruency in the Stroop colour naming task on flanker compatibility effects are not merely due to both tasks being selection tasks involving conflict. The word-reading task is as much a selection task as is the colour-naming task, but the two tasks differ in their recruitment of inhibition. The fact that the word reading task did not interact with the flanker task suggests that the crucial component of the Stroop task that caused the interaction with the flanker task is the inhibition of a dominant response, as is necessary on incongruent colour-naming trials, and not necessary on incongruent word-reading trials.

Are the observed carry-over effects of inhibition due to capacity limits or a switch cost?

As noted in Chapter 3, the persistence of the effects of inhibition in Task 1 over intervals of several seconds before Task 2 can be interpreted in different ways. One possibility is that inhibitory resources remain actively engaged in suppressing the response to Task 1 until the next occurrence of that task, so that these resources remain less available for suppression of response tendencies to distractors in Task 2 even after several seconds. This account involves the idea that inhibition mechanisms have a limited capacity, such that their engagement in one task limits their availability for another task.

Alternatively, it may be that for the inhibition mechanism that is engaged in Task 1 to subsequently engage in Task 2, a reconfiguration of the task-set of that mechanism must occur. The literature on switch costs shows that task-set reconfiguration cannot be fully carried out in advance, and that part of this reconfiguration must be triggered exogenously by the onset of the next task. Thus, a residual component of the switch cost will occur even with several seconds of preparation time allowed between the two tasks. The poorer distractor rejection observed after inhibition is engaged in making incongruent responses in Task 1 might therefore be due to a switch cost in the inhibition mechanism that was involved in those trials. That is, the need to re-configure the inhibition mechanism following its engagement in the incongruent (vs. congruent) condition of Task 1 could lead to a reduced ability to engage in inhibition of response tendencies to distractors in Task 2. This account does not involve the idea that inhibitory capacity remains actively engaged in suppressing responses to Task 1, rather: the switch cost is dependent on the fact that there is a need to switch from Task 1 to Task 2. The idea of a switch cost entails that access to the inhibition mechanism is impaired until the task set is properly configured. Thus, this account does not rely on the idea of inhibition mechanisms having a limited capacity. Interestingly, this account leads to the prediction that no carry over effects of inhibition should be observed in situations that do not involve a change in tasks. That is, carry over effects of inhibition of the kind observed in this thesis (i.e. which persist over several seconds of between-task interval) should not be observed between two trials of the same task. Future studies could be designed to test this prediction.

As also noted in Chapter 3, uncertainty as to which of these two accounts is more accurate does not alter the main suggestion of the present studies, namely that active response inhibition is involved in selective attention. Nonetheless, this issue does concern the fundamental nature of the observed effects. As such, a worthy aim for future studies would be to elucidate the precise nature of the processes responsible for the observed effects.

Implications from the present findings for the relationship between distractor interference and inhibition

In the present thesis, the observation of increased distractor interference in the flanker task following the engagement of inhibition in Task 1 suggests that distractors undergo less inhibition in these conditions. However, our findings do not imply that an increased distractor interference effect is *always* indicative of reduced distractor inhibition. Many studies in the NP literature have demonstrated that to the extent that NP reflects distractor inhibition, the relationship between interference and inhibition is far from straightforward, as prime-trial interference and probe-trial NP do not co-vary in a consistent manner.

As previously discussed in the general introduction, the relationship between NP and distractor interference may at least in part be influenced by the effects of the manipulations used on the processes of episodic retrieval involved in NP. As the observed effects in the present paradigm (of greater flanker interference following the engagement of inhibition in Task 1) are not dependent on a particular item being repeated from trial to trial (unlike in NP tasks, where the prime distractor item is repeated as the probe target), it seems unlikely that such processes of episodic retrieval could be in any way implicated by the present results.

Also, in the present experiments, the characteristics of the flanker task display remained constant across the conditions that did or did not involve inhibition in Task 1. Thus, the observed effects on distractor interference cannot be attributed to factors that directly alter the flanker task. Rather, the carry over effects seem only to be attributable to the change in processing in Task 1 induced by our manipulation of inhibition in that task.

In sum, while in our studies distractor interference may be taken as a reliable index of the efficiency of distractor inhibition, this clearly does not imply that the same is true of other studies in which distractor interference is measured.

Potential effects of engaging inhibition in one task on NP in a subsequent task

The experiments in this thesis involved a task in which inhibition may be engaged, followed by a single trial of a flanker task. A possible variation on this procedure would be to append *another* flanker task trial after the first flanker task trial, so as to enable the measurement of NP effects from ignored distractors in the first flanker task trial. To the extent that NP reflects processes of distractor inhibition, one might expect that the effect of engaging inhibition in Task 1 on NP in a subsequent flanker task should be to reduce the NP effect. Specifically, if the engagement of inhibition in Task 1 leads to a reduction in the inhibition applied to the distractor in a subsequent flanker task, as our studies suggest, then any NP effects observed when that distractor re-appears as a target in a following trial should be reduced in accordance with this reduction in inhibition.

However, this prediction is complicated by a consideration of the effects of greater distractor activation in the first flanker task trial (resulting from reduced distractor inhibition) on the probability of episodic retrieval of such distractors in the second flanker task trial. The NP literature shows that it is likely that NP reflects episodic retrieval processes to some extent (for reviews see e.g. Neill & Valdes, 1996; Tipper, 2001). In our paradigm, a reduction in distractor inhibition in the prime (i.e. the first flanker task trial) would entail those distractors being processed to a greater extent, which could in turn lead to a higher probability of episodic retrieval of those distractors in the probe (i.e. the second flanker task trial), and thus a higher level of NP. Thus, to the extent that retrieval processes are responsible for NP, a different prediction is suggested for NP measured in our paradigm. Thus there is not a clear unequivocal prediction regarding the effect of engaging inhibition in Task 1 of our paradigm on subsequent NP.

Inhibition, working memory, and cognitive control

The effects of working memory (WM) load on the processing of irrelevant information, as demonstrated both through behavioural measures (Lavie, Hirst, De Fockert and Colledge, 2002) and brain imaging (De Fockert, Rees, Frith & Lavie, 2001) show that inhibition is not the only factor that modulates selective attention performance in situations of low perceptual load. Our studies suggest that inhibition is responsible for suppressing inappropriate responses to distractors, but there must also be a mechanism responsible for determining which responses are appropriate and which are not. Lavie et al. (2002) and De Fockert et al. (2001)'s results suggest that WM is responsible for maintaining attentional priorities. Thus, inhibition and WM can be seen as two complimentary parts of the cognitive control system which keeps our behaviour in accordance with current goals and therefore ensures that responses are based on relevant rather than irrelevant stimuli.

The findings in this thesis highlight a functional similarity between inhibition and WM, as both have been shown to have similar effects on the efficiency of selective attention. Other studies have demonstrated further associations between WM and inhibition: Kane & Engle, (2002) found that subjects with lower WM capacity performed worse on a Stroop task than subjects with high WM capacity, suggesting that effective inhibition in the Stroop task depends on the availability of WM. Also, Mitchell, MacRae & Gilchrist (2002) demonstrated that imposing high WM load on subjects led to impaired performance of an antisaccade task (an inhibition-demanding task that is known to depend on the frontal cortex, as I discussed in the general introduction). Kane, Bleckley, Conway & Engle (2001) found that subjects with lower WM capacity performed worse on an antisaccade task than subjects with high WM capacity, while a prosaccade task elicited no group differences. These findings suggest that WM and inhibition might in fact draw from a common pool of control resources. The present research thus adds to a growing literature which may inform us as to the functional architecture of cognitive control processes.

Potential cross-modal effects of inhibition on distractor rejection

Further research may explore the effects of both stimulus modality and response modality on the effects of engaging inhibition in one task on distractor rejection in a subsequent flanker task. All the experiments presented in this thesis involve visually presented stimuli and manual key-press responses. It is possible, however, that the observed interaction between inhibition and selective attention occurs at a level that is not modality specific. This suggestion can be tested by using different stimulus modalities and/or response modalities.

Stimulus modality can be varied using, for example, auditory stimuli (e.g. different tones) as target stimuli and stop signals in a variation on the stop-signal task in Chapter 2. Similarly, tones presented to the right or left ears could be used in a variation on the spatial S-R mapping task in Chapter 3, such that subjects could respond either toward (congruently) or away from (incongruently) the source of stimulation. Also, an auditory analogue of the colour-word Stroop task could involve the words "loud" and "quiet" presented auditorily at relatively loud and quiet volumes, such that subjects respond to the volume of presentation and ignore the identity of the word itself. In all these suggested experiments it would seem that as long as manual responses are used, the change in stimulus modality should not reduce the effects of response inhibition in Task 1 on distractor rejection in the flanker task. That is, incongruent manual responses in the Stroop or spatial S-R mapping tasks, or stopped responses in the stop signal task, should lead to increased distractor interference in the flanker task, even with a change in stimulus modality between Task 1 and the flanker task.

A stronger test of potential cross-modal interactions between inhibition in one task and distractor interference in a subsequent task would be to vary the response modalities used. For example, in variations on all our experiments, a vocal response to the flanker task could be employed, such that the subject names aloud the target letter. Alternatively, vocal responses could be used in the stop signal, Stroop, and spatial S-R mapping tasks. For example, subjects could say "go" in response to the target in the stop signal task, and suppress this response when presented with a stop signal. Also, an eye movement response could be used in Task 1, for example an antisaccade task might provide an appropriate means of engaging response inhibition in order to examine potential cross-modal effects.

In all such tasks, if different response modalities were used in Task 1 and Task 2, then inhibition in Task 1 should lead to an increased flanker effect in a different modality *if* the inhibition responsible for the observed increase in flanker effects in our studies operates at a central level, and is not specific to the response modality.

Possible implications for real life

The main purpose of this research was to elucidate the mechanisms of selective attention used for distractor rejection. As selective attention plays a substantial part in our everyday lives, the implications of this broad endeavour are innumerable. There may also be direct implications from the particular findings shown here for particular situations in the real world. This research suggests that in situations where dominant responses must be suppressed, irrelevant information will be more disruptive to performance. For example, when driving on the other side of the road in a foreign country, the dominant response at every turning will be to join the side of the road that the driver is used to. This response has to be suppressed, and the present findings suggest that such suppression of dominant responses should lead to a reduced ability to prevent subsequent responses to irrelevant stimuli. This is just one example of the potential implications of the present findings to everyday life.

Conclusion

In conclusion, the research presented in this thesis provides a new line of behavioural evidence suggesting the involvement of active inhibition in selective attention. A new paradigm has been established in which the adverse effects of loading inhibition on subsequent selective attention performance have been shown to generalise across three inhibition tasks. Furthermore, the present work includes a specification and demonstration of the context necessary for the involvement of inhibition in selective attention, namely, low perceptual load. This paradigm may prove useful in further studies of the role of inhibition in selective attention, possibly along the lines of some of the suggestions made in this discussion. The findings from this new paradigm, taken together with the numerous alternative accounts that have been ruled out in the course of our experiments, converge with previous inhibition models of selective attention (e.g. Houghton & Tipper, 1994; 1998; Houghton et al., 1996; Tipper, 2001) to suggest that selective attention, in low perceptual load situations, is reliant on active inhibition.

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