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The Mechanisms of Proactive Interference and Their Relationship with Working Memory

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ABSTRACT

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Working memory (WM) capacity – the capacity to maintain and manipulate information in mind – plays an essential role in high-level cognitive functions. An important determinant of WM capacity is the ability to resolve interference of previously encoded but no longer relevant information (proactive interference: PI).

Four different mechanisms of PI resolution involving binding and inhibition have been proposed in the literature, although debate continues regarding their role. Braver et al. (2007) introduced an important distinction in the PI resolution literature, proposing two general types of PI control mechanisms that occur at different time points: proactive control (involves preparation in advance of the interference) and reactive control (occurs after interference occurs). This thesis proposed that among these four functions involving binding and inhibition, item inhibition and binding could be involved in proactive control, while familiarity inhibition and episodic inhibition could be involved in reactive control. The question is which mechanism in each pair is indeed involved in proactive control and reactive control respectively, and how these proactive control and reactive control mechanisms work together to resolve PI. In addition, do these mechanisms play a role in the relationship between PI resolution and WM?

In an individual differences study, individuals' ability to resolve PI was assessed in memory tasks, with two versions of each that encouraged the use of either proactive or reactive control. In addition, measures were obtained of individuals' ability of binding and inhibition in

tasks that had minimal memory demands. Regression analyses showed contributions of binding and inhibition to PI resolution and WM. Moreover, these functions are responsible for the correlation between PI resolution and WM. In a neuroimaging study, the neural basis of proactive control was examined by comparing two memory tasks that differed in their demand on binding and inhibition. In addition, the brain regions engaged in reactive control was examined by contrasting trials involving interference or not. The thesis showed that item inhibition carried out by the left inferior frontal cortex (IFC) is involved in proactive control while episodic inhibition carried out by the left IFC and the posterior parietal cortex is involved in reactive control.

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Chapter 1. Introduction

Working memory plays an essential role in higher-level cognitive functions, such as sentence comprehension, problem solving, reasoning, and academic performance (SAT scores) (e.g., Conway et al., 2005; Daneman & Carpenter, 1980; Daneman & Hannon, 2001; Daneman & Merikle, 1996; De Beni, Borella, & Carretti, 2007; Kyllonen, 1996). In addition, a decrease in working memory (WM) capacity has been considered as the major cause of cognitive decline during normal aging (e.g., Salthouse, 1996). Some previous findings indicate that susceptibility to information that is previously encoded but not longer relevant (proactive interference: PI) is at least one important determinant of WM capacity (e.g. Chiappe, Hasher, & Siegel, 2000; Conway & Engle, 1994; Kane & Hasher, 1995; Rosen & Engle, 1998; Whitney, Arnett, Driver, & Budd, 2001). This dissertation aimed to investigate the mechanisms underlying the resolution of PI and their roles in the relationship between PI and WM.

1.1. Control and Regulation of WM.

Despite the fact that different models of WM hold very distinct assumptions about the mechanisms involved in WM and the relationship between WM and long-term memory (LTM), all models assume some control and regulation aspect of WM. For example, control and regulation mechanisms have been proposed to coordinate storage in modality-specific systems (Baddeley & Hitch, 1974; Baddeley & Logie, 1999), allocate attention among different embedded memory components (Cowan, 1988; 1995; 2000), sustain activation in the face of distracters (Engle, Kane and Tuholski, 1999), or inhibit irrelevant information (Hasher & Zacks, 1988). Additionally, cognitive control has also been assumed to be the source of limitations and individual differences in WM (Engle et al., 1999; Hasher & Zacks, 1988; Kane, Hambrick, Tuholski, Wilhelm, Payne, & Engle, 2004). Since the correlation between PI resolution and WM

has often been considered as evidence for the role of cognitive control in WM, I will first review two WM models that emphasize a control component of WM. They are resource-limited controlled attention theory and inhibitory efficiency account.

1.1.1. Resource-limited controlled attention. The resource-limited controlled attention theory has been proposed by Engle et al. (1999; Engle, Conway, Tuholski, & Shisler, 1995; Unsworth & Engle, 2007) to interpret findings from studies examining individual differences in WM. These studies found that differences between high and low WM capacity individuals (categorized by performance on complex span tasks[1]) were only observed when interference and conflict was involved in the tasks (Conway & Engle, 1994; Kane, Bleckley, Conway, & Engle, 2001; Unsworth, Schrock, & Engle, 2004; Kane & Engle, 2000), suggesting that the ability to resolve interference may determine WM capacity.

Consistent with these findings, the resource-limited controlled attention theory postulated that individual differences in WM reflect variation in the capacity to attentionally control and regulate WM processes, but do not result from differences in the amount of information an individual can store and process. Controlled attention is mainly involved in two processes: maintaining information in the focus of attention (contains attended information that is the most completely activated, and can be directly accessed) and retrieving information from the short-term store (a portion of long-term memory but outside the focus of attention; where access to information is still reliable but requires a retrieval process). Because the focus of attention can

[1] Typical complex span measures involve two tasks – one that emphasizes processing (such as solving an arithmetic equation or judge whether a sentence is sensible or anomalous) and one that emphasizes storage (such as maintaining a letter that follows each equation or remembering the last word of each sentence). Complex span tasks place more demands on control processes that coordinate the two tasks. In contrast, simple span tasks, such as recall of numbers that were just presented, involve only one task, and thus are usually used to measure short-term memory storage and processing.

only maintain a fixed number of items (a maximum of 4 in recall tasks; Cowan, 2000), information in the focus of attention will be replaced by salient stimuli that attract exogenous attention or new incoming information that exceeds the capacity limitation. When information that is about to be replaced is still task-relevant, controlled attention is needed to resist the interference of distracting information and maintain the original information. Or, when information that has already been replaced from the focus of attention is once again needed, controlled attention helps to retrieve the information from the short-term store.

For example, high and low WM capacity individuals differ in their ability to use contextual cues to restrict retrieval from the short-term store to only relevant items. One piece of evidence for this claim comes from Oberauer (2005) who measured individual differences in a local and a color recogniton task. In the color recogniton task, subjects were asked to determine whether an item (the probe) appeared in a previously visually presented list (e.g., in the trial "LIST– *cake, shoe, vase, lamp*; PROBE – *shoe*", a positive response is required). Oberauer assumed that an automatic process detecting the familiarity level of the probe was sufficient for meeting the task goal. In contrast, in the local recognition task, subjects had to judge not only whether the probe (presented at one of the locations where the words were presented in the list) was in the list, but also whether it was at the same location as in the list. This task requires a recollection process that involves controlled retrieval based on contextual cues, in this case, the locations. If this contextual-based recollection process cannot successfully restrict retrieval targets to relevant information (i.e., in this case, the word in the list that is at the same location as the probe), irrelevant information (i.e., words in the list that are at different locations from the probe) will cause interference. Since the interfering words were initially relevant when presented in the list, and become irrelevant when the contextual cue (presented at a particular location) is

provided, the interference they cause is termed proactive interference (PI). The study of Oberauer (2005) found that individual differences in WM measured in complex and simple span tasks were only correlated with performance on the local recognition task that involved resolution of PI but not on the global recognition task that required an automatic familiarity process. This finding again suggests that individual differences in WM depend on the ability to resolve PI. Moreover, individuals with low WM capacity produced more errors resulting from intrusions of irrelevant information (i.e., making a positive response when the probe is in the list but at a different spatial position) in the local recognition task than individuals with high WM capacity. This result provides direct evidence for the assumption that variation in controlled retrieval based on contextual cues is responsible for individual differences in WM.

1.1.2. Inhibitory efficiency account. A similar view that emphasizes controlled attention is the inhibitory efficiency theory by Hasher and Zacks (1988). Consistent with the controlled attention account, the inhibitory efficiency theory does not postulate that the amount of information that can be maintained and processed in WM is the source of individual differences. This theory presumes that all encountered information automatically generates activation in WM at the early stage, and thus there are few limitations or individual differences in the amount of automatic activation in WM. However, immediately following the initial automatic activation, controlled attention and executive functions driven by task goals come into play, including both an excitatory mechanism to increase the activation of task-relevant information and an inhibitory mechanism that suppresses the activation of irrelevant information.

On the other hand, this theory differs from the general controlled attention account (Engle et al., 1999) in terms of its emphasis on the role of inhibitory processes. The importance of inhibition arises from research findings on aging from Hasher and colleagues (Hamm & Hasher,

1992; Hasher & Zacks, 1988; Zacks & Hasher, 1994; Yoon, May, & Hasher, 2000). For example, young and old adults were found to differ in tasks that specifically require inhibitory functions, such as negative priming tasks (in which a person must respond to the target and ignore the distractor[2]; Hasher & Zacks, 1988; Zacks and Hasher, 1994), and tasks involving comprehension of garden-path sentences (in which an initial interpretation of a sentence has to be suppressed; Hamm & Hasher, 1992). In contrast, young and old adults exhibited comparable effects in tasks reflecting automatic activation, such as the semantic priming effect (i.e., the effect that processing of a word automatically facilitates access to its semantically related word; Cameli & Phillips, 2000; Giffard, Desgranges, Kerrouche, Piolino, & Eustache, 2003). Moreover, additional findings showed that the performance of older adults varies along with circadian arousal patterns in tasks involving inhibitory functions, but not in tasks tapping excitatory control processes, such as making GO responses in GO/NOGO task (Yoon et al., 2000).

Furthermore, the inhibitory efficiency theory (Lustig, Hasher, & Zacks, 2007; Hasher, Zacks, & May, 1999) postulates three types of inhibitory control. These include preventing irrelevant information from entering the focus of attention (Access), deleting information that is previously relevant but not any more from the focus of attention (Deletion), and suppressing dominant responses that are inappropriate to current task goal (Restraint). For PI resolution that is closely related to WM capacity (Engle, et al., 1999; Friedman & Miyake, 2004; Oberauer, 2005), a deletion inhibitory control seems to be beneficial (Hasher, Chung, May & Foong, 2002). That is, to resolve interference of previously encoded information, an inhibitory control process

[2] Presumably, the to-be-ignored distractor stimulus is inhibited when participants respond to the target. The level of inhibition can be measured when the to-be-ignored stimulus on one trial becomes the target on the next. If the to-be-ignored stimulus was greatly inhibited, participants take longer to respond to it when it becomes a target.

deletes the interfering information from memory as soon as it can be identified as irrelevant. In line with previous findings disadvantages in inhibitory control for older adults, they are less efficient in deleting irrelevant information and thus more susceptible to PI (Hasher et al., 2002; Ikier, Yang, & Hasher, 2008). Consistent with the idea of separable inhibitory functions, Friedman and Miyake (2004) found that although prepotent response inhibition (e.g., withholding a response when a stop-signal occurs; or Restraint according to Hasher et al., 1999; Hasher, Lustig, & Zacks, 2007) and resistance to distractor interference (e.g., naming a target word that is presented with a distractor word; or Access) were closely related, both were unrelated to resistance to PI (i.e., rejecting information that is previously relevant but has since become irrelevant; or Deletion). More importantly, between these two inhibitory factors, only the ability to resist PI was related to performance on a complex span task that is often used to measure WM capacity. This finding suggests that the inhibitory function involved in PI resolution (e.g., deletion) is the one that determines WM capacity.

1.1.3. Framework for the thesis. To summarize, the two theories – the resource-limited controlled attention theory and the inhibitory efficiency account both propose that a controlled attention process involved in PI resolution is a crucial aspect of WM and mediates the close relationship between PI and WM. These two theories, however, differ in the assumptions of which particular function is involved in PI resolution. The inhibitory efficiency account emphasizes the role of an inhibitory function, whereas the resource-limited controlled attention theory does not postulate a particular function for PI resolution, but instead assumes this control process requires a general attentional resource.

In addition, based on the reviewed models, the present thesis adopted the idea that WM includes the focus of attention and the active portion of LTM. The focus of attention holds very

limited information that is highly activated to support on-going processing. The active portion of LTM is outside the focus of attention, and information in the active portion of LTM has to be retrieved with the assistance of proper cues as needed.

1.2. Proactive Interference (PI)

1.2.1. Proactive Interference (PI) and WM. As discussed earlier, an important role of controlled attention or, more specifically, inhibition has been postulated in several approaches to working memory. One type of inhibition that has been proposed is the ability to delete from working memory information that was relevant but is no longer (Friedman & Miyake, 2004; Hasher et al., 2002). An inability to do so results in proactive interference (PI) which consists of the intrusion of previously encoded but no longer relevant memory representations. Resolution of PI therefore has often been assumed to engage a process of inhibition. Performance on PI tasks is also commonly considered to be an indicator of inhibitory functions (Friedman & Miyake, 2004; Hasher et al., 2002; McCabe, Roediger, McDaniel, Balota, & Hambrick, 2010; Salthouse, Atkinson, & Berish, 2003). Nevertheless, deletion of no longer relevant memory representations does not seem to be the only inhibitory function that can resolve PI (Badre & Wagner, 2005; Jonides, Smith, Marshuetz, & Koeppe, 1998; Jonides & Nee, 2006; Nee, Jonides, & Berman, 2007). In addition, since PI tasks usually involve episodic memory (for example, whether the probe appeared in the most recent list or whether the probe appeared in the list written in the same color or at the same location - Badre & Wagner, 2005; Oberauer, 2005), an ability to assign item information to its contextual source may also be critical. Indeed, a process of linking encoded item information to its contextual source (termed binding), without involving any inhibitory function, has also been proposed to resolve PI (Oberauer, 2005). Understanding which of these processes plays a role in PI resolution is important for interpreting individuals'

performance on PI tasks.

Moreover, a close relationship between resolution of PI and memory has been repeatedly demonstrated. Keppel and Underwood (1962) first found that it was the learning of prior information that was responsible for forgetting, but not the decay of memory. Moreover, the correlation between PI and WM has been shown in various individual differences literatures. For example, Whitney et al. (2001) found that susceptibility to PI predicted performance on working memory span tasks. Also working memory span is a good predictor of the ability to resolve PI (e.g. Chiappe, et al., 2000; Conway & Engle, 1994; Friedman & Mikaye, 2004;Rosen & Engle, 1998; Whitney et al., 2001; Oberauer, 2005; Oberauer, Lange, & Engle, 2004). Furthermore, older adults who generally demonstrate reduced WM capacity are far more vulnerable to PI than younger adults (Kane & Hasher, 1995). These findings indicate that the ability to resolve PI is at least one important determinant of WM capacity. Therefore, understanding the mechanisms of PI resolution may also clarify the nature of WM.

The goal of this thesis is to examine which function – i.e., inhibition or binding is indeed involved in PI resolution and whether the function(s) could explain the close relationship between PI resolution and WM.

1.2.1. Mechanisms of PI resolution. As discussed, one mechanism that has often been considered as a function that resolves PI is inhibition (e.g., Friedman & Miyake, 2004; Hasher & Zacks, 1988). Consider one typical PI task, the recent negatives paradigm, as an example. In each trial of a short-term recognition probe task, subjects are presented with a list of letters. Then after a short delay interval following the disappearance of the list, they are asked to identify whether a probe letter appeared in the current list. When the probe appeared in the preceding list but not the current list (termed a “recent negative”; see Figure 1.1a for an example), subjects take

longer to reject the probe than when a negative probe did not appear in any previous lists (termed a “non-recent negative”; see Figure 1.1b for an example). The PI effect is measured by subtracting the response times for non-recent from recent negative trials. Different theories involving an inhibitory function have been proposed to account for PI resolution in this task.

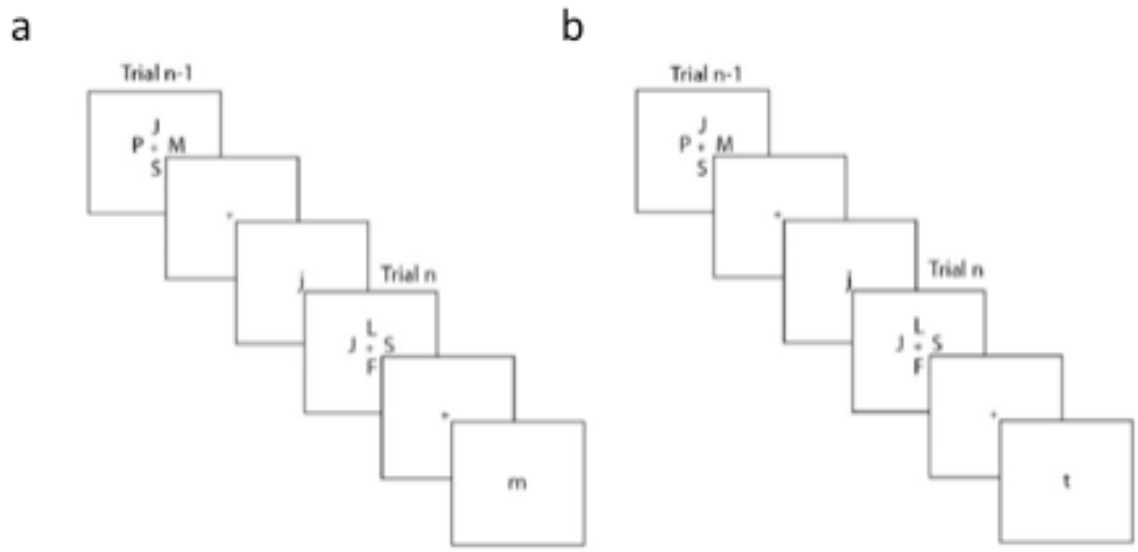

Figure 1.1. a) recent negatives trial in the recent negatives task; b) non-recent negatives trial in the recent negatives task. Adopted from Jonides & Nee (2006).

Before discuss the inhibitory process that is involved in PI resolution, it is important to understand how participants make accurate responses and how the interference occurs. Previous studies have suggested that two processes, familiarity and search are involved simultaneously in recognition tasks where participants are asked to judge whether a probe appeared in a previous to-be-remembered list (Atkinson, Herrmann, & Wescourt, 1974; also see Mandler, 1980; Jacoby, 1991). The search process is an effortful process that goes through the entire search set (constituted by all relevant items that are consistent with the task goal). In the example of the recent negatives task, items from the current list constitute the search set (e.g., “L, J, F, S” in trial n in Figure 1.1a). The probe is checked against the search set to determine if a match is found. If

the probe matches any member in the search set, a positive response can be made. Otherwise, a negative response is appropriate. Moreover, due to the limited amount of information that can be maintained in the focus of attention, the search set will need to be retrieved before the search process starts. In contrast, familiarity is a fast and automatic process. The probe would be matched in parallel across items in memory to determine its activation level in memory. The activation level reflects how frequently and how recently an item has been accessed. Therefore, a high level of familiarity indicates that the item has been recently accessed, and thus should be associated with a positive response (and a low level with a negative response). Although the two processes (search and familiarity) usually generate consistent conclusions for recognition, for the recent negatives trials, search and familiarity provide conflicting responses. Based on the search process, the recent negative is not a member of the current list, and thus is associated with a negative response. However, since the recent negatives have a high level of familiarity, they are also associated with a positive response. To resolve the response conflict for recent negatives, an inhibitory function is proposed by a familiarity-inhibition account (Jonides et al., 1998, 2006; D'Esposito, Postle, Jonides, Smith & Lease, 1999). Since the search process guarantees correct responses (e.g., in this example, whether the probe is a member of the most recent list), when the conflict between responses is detected for the recent negatives, the positive response generated by the high level of familiarity will be suppressed. I will term this inhibitory function **familiarity inhibition**.

Not all explanations of the recent negatives effect, however, assume that familiarity and a conflict between opposing responses are the source of the effect. According to another account for the recent negatives effect, the episodic retrieval account (Badre & Wagner, 2005; Nee et al., 2007), familiarity does not contribute directly to a recognition decision. Rather, recognition

judgments solely rely on a search process. More importantly, this approach emphasizes the association between relevant items and their contextual source, i.e., the relevant context. In PI tasks, items are only considered relevant if they are associated with a required context (e.g., in the current list for the recent negatives task). Therefore, to conduct a search, the required context serves as a contextual cue with which relevant items can be retrieved. Once the relevant items are retrieved, they form the search set where the search process can operate. If a strong association between the context and the relevant items was constructed during encoding, the relevant items can be easily retrieved and the search process will be efficient. If this association, however, is not strong, the search set cannot be retrieved as easily, and the search process will be disturbed. The PI effect arises in this situation because the search process is more disturbed for interfering trials than for non-interfering trials. Interfering trials involve irrelevant information that results in extra difficulty in making a correct item-context association. For example, for words that are presented as recent negative probes, an appropriate link to its accurate contextual source (i.e., the context of the preceding list) and an inappropriate link to the inaccurate contextual source (i.e., the context of the current list) might be both encoded and maintained since the two lists are presented closely in time. When these words are presented as recent negative probes, as opposed to generating a conflicting response directly, the high familiarity level of the probe automatically triggers the activation of the appropriate link and inappropriate link. The conflict between the two contextual sources makes it more difficult to build the correct association and form the correct search set. Although the episodic inhibition account attributes PI to very different representations from the familiarity-inhibition theory (irrelevant episodic information vs. response conflict), it does assume that the conflict between relevant and irrelevant contexts must be resolved through a biased selection process once the interference is

detected (Jonides & Nee, 2006; Nee et al., 2007). This biased selection process may involve an excitatory process that increases the activation of the relevant contextual information or/and an inhibitory process that inhibits the activation of the irrelevant episodic information (Kan & Thompson-Schill, 2004). Since the present study does not aim to distinguish the excitatory and the inhibitory processes, I will assume the inhibitory process to be the underlying mechanism of the biased selection. I will term this inhibitory function **episodic inhibition**. Finally, once interference is resolved for the recent negative trials, relevant items can be retrieved with the context cue and the search process can proceed.

Although based on different assumptions on how interference occurs, the previous two inhibitory functions both resolve PI after the interference effect is detected. Therefore, they both function in PI resolution reactively. Interestingly, Braver, Gray and Burgess (2007) proposed a dual mechanism cognitive control (DMC) model consisting of two control mechanisms, a reactive control process as proposed in the previous two accounts and a proactive control process that was overlooked by many studies on PI resolution. These two control mechanisms cooperate in resolving PI at different stages relative to the occurrence of conflict. Specifically, proactive control takes place during encoding and during the retention period between the list and probe presentations. Moreover, proactive control is a process of consistently sustaining the task goal and task-relevant information to prevent any interference from happening in advance of critical events (e.g., presentations of recent negative probes). Therefore, proactive control is engaged for all trials in a PI task, rather than only for trials that involve conflict (e.g., recent negative trials). In contrast, reactive control comes into play when conflict has already been detected once an interfering probe (e.g., a recent negative) is presented. Therefore, reactive control acts in a transient manner rather than continuously, and is only involved for interfering trials.

Additionally, regarding the relationship between proactive and reactive control, when proactive control is applied, PI will decrease and thus the demand for reactive control will be reduced. In contrast, if proactive control is not effectively applied, more reactive control will have to be engaged once interference occurs (Braver et al., 2007). The DMC model has been supported by both neuroimaging and individual differences findings (Braver et al., 2007; Braver, Paxton, Locke, & Barch, 2010; Burgess & Braver, 2010; Paxton, Barch, Racine, & Braver, 2008).

The possible functions involved in reactive control of PI resolution were discussed earlier, but what would be the functions involved in proactive control? Only one study so far has examined proactive control in the recent negatives task (Oberauer, 2005). Although the distinction between proactive control and reactive control was not clearly laid out in this study, the functions that were examined should be considered as proactive control mechanisms according to the DMC model. In this study, Oberauer (2005) proposed two processes that prevent PI from occurring even before any probe is provided. The first mechanism is again an inhibitory function. However, this inhibitory function inhibits a different type of information than that involved in reactive control. Specifically, this inhibitory function deletes unrelated items from WM (Hasher et al., 1999), instead of inhibiting an inappropriate response tendency or inappropriate item-context association. In the example of the recent negatives task, inhibition could be used to erase items from the preceding list from memory when moving on to the current list. Because activation of items in the preceding list was inhibited, they cannot generate a positive familiarity-based response any longer. Then, consistent with the idea that response conflict causes PI (i.e., the familiarity inhibition theory), when an item in the preceding list is presented as the probe, only a correct negative response will be generated and thus potential interference will be prevented. To distinguish this inhibitory process from the two inhibitory

processes introduced previously (i.e., familiarity inhibition and episodic inhibition), I will term it **item inhibition**.

Interestingly, the second mechanism Oberauer (2005) proposed is a function that does not involve inhibition but involves building associations between items and contextual information – such as the list containing the item or the spatial location of the item. This function is called the binding function. Similar to the assumption of the episodic retrieval account, if items are bound strongly to their contextual features during retention, relevant items can be easily retrieved with the contextual cue (for the recent negatives task, whether the probe appeared in the most recent list; or, for this study, more specifically, whether the probe appeared in the list written in the same color or at the same position; Badre & Wagner, 2005; Oberauer, 2005), and the inappropriate association with inappropriate contextual source would be very weak and cannot cause much interference. Correct responses then are guaranteed by the search process and are easy to make even when irrelevant information is present. Therefore, strong binding strength prevents upcoming interference. In contrast, if the binding strength is not strong enough, irrelevant information will lead to interference. Therefore, both the binding process and the inhibitory process can prevent interference from arising prior to the presentation of the probe. Examining which function is indeed involved in PI resolution will help evaluate whether the current emphasis on the inhibitory function is warranted.

To summarize, a binding process and an item inhibitory process have been postulated to prevent upcoming interference before a probe is presented. In addition, a familiarity inhibitory function or an episodic inhibitory function have been assumed to resolve ongoing interference occurring after the interfering probe is presented. Interestingly, although proposed separately, the binding hypothesis seems to be related to the episodic inhibitory process because they both

emphasize context-item associations. On the other hand, the item inhibitory process and the familiarity inhibitory process both resolve PI based on the assumption that a high familiarity level of recent negatives causes the interference. Considering these links, it may be possible to associate the two related processes in the same model of PI resolution.

Using the DMC model, we can first associate the binding process and the episodic inhibitory process. According to the episodic retrieval account, interference occurs between appropriate and inappropriate contexts, because both of them can link to the recent negative probes. However, if the binding strength built between items and appropriate contextual sources during encoding and retention is high, interference from an inappropriate context can be resisted. The process that binds the appropriate context and items during retention is the binding function from Oberauer (2005). Since this binding function is involved during retention and able to prevent PI even before a probe is presented, it matches descriptions of proactive control in the DMC model. In contrast, the episodic inhibitory process inhibits the inappropriate context when PI has already arisen, consistent with the properties of a reactive control mechanism. Thus, one model of PI resolution may be proposed that focuses on episodic memory – specifically, in the association between item and context – and which involves a proactive control mechanism (binding) and a reactive control mechanism (episodic inhibition). I will term this hypothesis as **the binding-episodic inhibition account**.

On the other hand, the item inhibitory control mechanism from Oberauer (2005) seems to be linked conceptually with the familiarity inhibitory function. According to the familiarity inhibition account (Badre & Wagner, 2005; Nee et al., 2007), PI results from response conflict caused by a high familiarity level of interfering probes. If the interfering items can be inhibited before a probe is presented, the familiarity response to recent negatives that interferes with the

correct negative response will not be elicited. Thus item inhibition that deletes irrelevant items during retention periods prevents upcoming interference as a proactive control mechanism. If, however, irrelevant items cannot be effectively inhibited by the item inhibitory process, interference will occur once an interfering probe is presented. To resolve the interference, familiarity inhibition will then inhibit the incorrect positive response. Since familiarity inhibition functions as needed, it is a reactive control mechanism. I will refer to this second model related to familiarity as **the dual inhibition account**.

To summarize, two DMC models are proposed (see Figure 1.2). They are the binding-episodic inhibition account and the dual inhibition account. According to the binding-episodic inhibition account, a binding function is involved in proactive control, and an episodic inhibition function acting on item-context binding is the reactive control mechanism. In contrast, the dual-inhibition account assumes an item inhibitory process as the proactive control mechanism, and a familiarity inhibitory process as the reactive control mechanism.

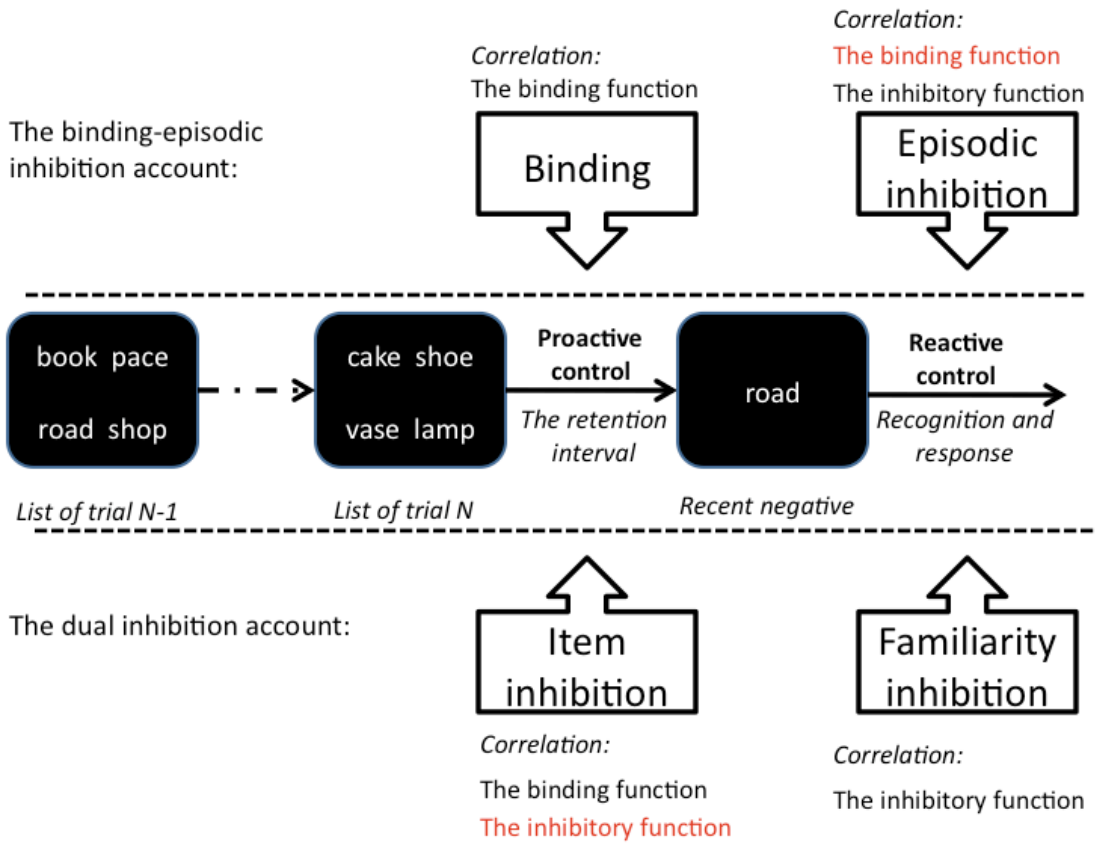

Figure 1.2. A graphic depiction of the binding-episodic inhibition account and the dual inhibition account.

Between the two DMC accounts, more evidence supports the binding-episodic inhibition account. Neuroimaging studies have compared neural activations for different types of trials (positive, recent negative, and non-recent negative) in the recent negatives task (Badre & Wagner, 2005; Nee et al., 2007). Since only demands for reactive control but not for proactive control differ between recent and non-recent negative trials, these neuroimaging findings would shed light on the mechanism of reactive control. According to both the binding-episodic inhibition and the dual inhibition account, recent negative trials (where interference occurs) should elicit greater activation than non-recent negative trials (trials do not involve any interference) in regions responsible for reactive control, either episodic inhibition or familiarity inhibition respectively. In contrast, for the comparison of another pair of trial types - recent positives vs. non-recent positives, these two accounts produce different predictions. A recent

positive refers to a probe that is a member of the current trial and thus requires a positive response, but also has appeared in the preceding trial. A non-recent positive, in contrast, is a probe that is a member of the current list but has not been seen in the preceding trial. According to the dual inhibition theory, a familiarity inhibitory process of reactive control is needed when response conflict is detected for the recent negatives. However, for recent positive trials, because both the high level of familiarity and a search process result in positive responses, no such familiarity inhibitory process is needed. Therefore, regions involved in familiarity inhibition should show more activation for the recent negative trials than for all other types of trials whose activation levels should not differ. However, this prediction was not upheld. In some regions of the prefrontal cortex, greater activation was seen for both recent negative trials and recent positive trials relative to non-recent trials. The episodic inhibition account outperforms the inhibition-familiarity account in explaining this finding. Based on the episodic inhibition account, the high level of familiarity of both recent negative and recent positive probes triggers the retrieval of the context of the preceding list which causes interference in searching for items with the correct contextual association. Thus, even though a recent positive is a member of both the relevant and irrelevant lists, the existence of the multiple sources of contextual information still induces interference, consistent with the sensitivity of regions in the prefrontal cortex to both types of recent trials.

Another piece of evidence for the binding-episodic inhibition account is from an individual differences study examining the binding and item inhibitory functions of proactive control. Oberauer (2005) compared the performance of individuals with different WM capacity in two recognition tasks. One of these tasks is a version of a PI task that could involve either binding or item inhibition as mechanisms of proactive control during retention intervals. (WM

capacity was measured in span tasks. Low capacity individuals include two groups: low capacity young adults and old adults.) In the other task, only the binding function would be useful during retention intervals. This study found similar correlations between PI the effect and age/WM capacity for both tasks, indicating that the two tasks engage the same proactive control process - which is binding.

To summarize, some evidence has supported the binding-episodic inhibition account. An individual differences study provided evidence for the binding theory as a proactive control mechanism and findings from neuroimaging studies are consistent with the idea of episodic inhibition being a reactive control mechanism. Nevertheless, none of the studies has examined proactive and reactive control with the same approach, either using neuroimaging or an individual differences approach. In the first study of this thesis, the mechanisms involved in proactive control and reactive control was examined using the same approach – i.e., an individual differences approach. The second study was a neuroimaging study that examined the same issue and the neural basis of PI resolution.

Chapter 2. Individual Differences in PI Resolution

In a typical PI task, such as the recent negatives task discussed in the earlier section, the behavioral indicator of PI resolution is the difference in performance between the interference trials and the control trials (i.e., the PI effect). This indicator reflects the efficiency of both proactive control and reactive control, since these two types of control mechanisms could both reduce the difficulty of rejecting the interfering probes. Therefore, to examine the mechanisms involved in proactive control and reactive control respectively, the PI tasks need to be designed to promote the use of proactive control or the use of reactive control. Then even though the PI effect would still reflect the efficiency of both control mechanisms, it would mainly be an indicator of proactive control in the PI tasks promoting the use of proactive control or mainly an indicator of reactive control in the PI tasks promoting the use of reactive control. A method of varying the involvement of proactive vs. reactive control was proposed by Braver et al. (2007). According to the DMC model (Braver et al., 2007), proactive control can prevent upcoming PI but is more resource-demanding. Therefore it plays a role only when interference is likely to be large and costly unless proactive control is employed. Specifically, proactive control can be promoted by including a high proportion of interfering trials in the task. In contrast, reactive control is a post-conflict control and only functions as needed, so it comes into play when there are few interfering trials and proactive control is too costly to be engaged to prevent the potential PI. Therefore, reactive control would be more dominant when the proportion of interfering trials is low. In the present study, two versions of PI tasks were used – a version with a high proportion of interfering trials promoting proactive control and a version with a low proportion of interfering trials promoting reactive control. Then, two series of confirmatory factor analyses were conducted on the measures of proactive and reactive control of PI resolution to compare the

fit of models: a model consisting of a single factor extracted from all PI tasks and a model consisting of two factors extracted from PI tasks with a high proportion of interfering trials and PI tasks with few interfering trials respectively. If there are distinct proactive and reactive control mechanisms, the two-factor model should have a significantly better fit than the one factor model. If distinct proactive and reactive control mechanisms do not exist, the one factor model should be sufficient.

Given that different proportions of interfering trials promote different mechanisms in PI resolution (i.e., proactive control vs. reactive control), the findings of Oberauer (2005), described earlier, need to be revisited. Two tasks were compared in his study. One of these tasks (i.e., directed forgetting in which subjects are instructed to forget a subset of encoded items) is a version of a PI task that could involve either binding or item inhibition as mechanisms of proactive control during retention intervals. In the other task (ie., local recognition in which subjects must remember the location in which an item was presented), only the binding function would be useful during retention intervals. The results of this study showed comparable age differences and comparable differences between two young adult groups (high WM vs. low WM) in both the directed forgetting and the local recognition task (Oberauer, 2005). The author claimed that these results suggested that the same function, i.e., binding was involved in both tasks, because only binding can be involved as the mechanism of proactive control in both tasks. In addition, individuals' performance on the directed forgetting task was not correlated with WM capacity when their performance on the local recognition task was controlled for. However, this conclusion overlooked the fact that both tasks might also rely on an inhibitory process as a reactive control mechanism to resolve the PI that proactive control did not prevent successfully. Indeed, in this study the proportion of interfering trials (i.e., the intrusion trials) was relatively

small (25%). According to the assumption of the DMC model, proactive control may not even be involved in this situation. In contrast, reactive control should more important for PI resolution in this task. Thus, the comparable sizes of correlations between PI task performance and WM capacity in both tasks may actually reflect the involvement of the same reactive control process, i.e., inhibition, and the role of the inhibitory process in WM. Therefore, this study did not provide strong evidence that binding serves as the predominant proactive control mechanism. Thus, it is still a question whether binding as a proactive control mechanism or inhibition as a reactive control mechanism is related to WM.

Therefore, in addition to measuring whether there are separate proactive control and reactive control, in the present study binding and inhibitory ability was measured directly in tasks that logically require only binding or only inhibition. Then, performance on pure binding and pure inhibition factors was correlated with performance on PI tasks with different proportions of interfering trials to examine which function, binding or inhibition is involved in proactive and reactive control of PI resolution. In particular, the aim of the present study was to test the binding- episodic inhibition account and the dual inhibition account of PI resolution.

If the binding-episodic inhibition account is correct, binding should be involved as the proactive control function and episodic inhibition should serve as the reactive control mechanism. More specifically, performance on binding tasks (tasks that only require a binding function) should be correlated with performance on PI tasks with a large proportion of interfering trials (which primarily measures proactive control). Performance on inhibition tasks (tasks that only require an inhibitory function) should be correlated with performance on PI tasks with few interfering trials (which measures reactive control). Moreover, the performance on the binding tasks should also predict performance on the PI tasks with few interfering trials (which measured

reactive control). This prediction seems counter-intuitive at first, because participants should not engage in much proactive control (in which the binding process may play a role) in the PI tasks with few interfering trials (which primarily engage reactive control). However, even though the item-context binding relations may not have been focused on during the retention interval as proposed in the binding account of proactive control, these binding relations had to be encoded during the list presentation to meet the task goal. In addition, since the binding-episodic inhibition account assumes that PI arises due to the interference between appropriate and inappropriate contextual information, how well participants could encode the binding relations determines how much interference would arise and needs to be resolved by the inhibitory function reactively. With the same level of ability of inhibition, participants with better performance in the binding tasks would have less interference to be resolved.

In contrast, if the dual inhibition account is correct, item inhibition should be involved in proactive control and a familiarity inhibitory function should be involved in reactive control. Since both item inhibition and familiarity inhibition are inhibitory functions, performance on inhibition tasks should be correlated with performance on all PI tasks including those measuring proactive control and those measuring reactive control. Performance on binding tasks, however, should also be correlated with performance on PI tasks with a large proportion of interfering trials (which measured proactive control). The reason is that although the binding relations are not actively maintained during proactive control, the association between items and contextual information has to be encoded to guide the item inhibitory function. Otherwise, the inhibitory function would not "know" which items to inhibit. By contrast, the binding function should not correlate with performance on PI tasks with a low proportion of interfering trials (which measured reactive control), since the dual inhibition model assumes that interference arises due

to response conflicts but not conflicts between binding relations.

Therefore, the differences that could distinguish the two DMC models include first whether an inhibitory function is involved in PI tasks with a large proportion of interfering trials that measure proactive control. If the answer is positive, it would support the dual-inhibition model. If inhibition is not involved in proactive control, it would support the binding-episodic inhibition model. The second distinction between the two models is whether a binding function is involved in the PI tasks with a low proportion of interfering trials that measure reactive control. If binding is indeed involved in reactive control, this result would support the binding-episodic inhibition model; if not, the finding would support the dual-inhibition model). The functions that should be correlated with proactive control and reactive control respectively according to each model are summarized in Figure 1.2.

Another important question, in addition to those concerning the mechanisms involved in PI resolution, is whether proactive or reactive control is more important for individual differences in WM capacity. Braver et al. (2007) assumed that proactive control is more costly of resources, because proactive control is sustained during the entire retention interval. Such extended periods of neural activation require additional metabolic resources (Braver et al., 2007). In contrast, reactive control is transient and requires fewer resources. If all cognitive functions rely on a general controlled attentional resource (i.e., the resource-limited controlled attention theory**;** Engle et al., 1999; Engle, Conway, Tuholski, & Shisler, 1995), proactive control that more intensively taps the capacity of this cognitive resource might be more crucial in explaining individual differences in WM and high-level cognitive functions than reactive control regardless of the particular function involved in these processes (Braver et al., 2007). Braver et al. (2007) divided participants into two groups according to their general fluid intelligence (gF; measured

by the Ravens Advanced Progressive Matrices Test). The results showed that high gF individuals exhibited reduced PI interference than low gF group, but only in the block in which proactive control was promoted, indicating that individual differences in gF reflects different levels of abilities to implement proactive control but not reactive control. Since WM capacity is highly correlated with gF, it is possible that individual differences in WM are as well driven by variation in proactive control rather than reactive control.

Other approaches suggest that both proactive and reactive control could relate to WM capacity. As discussed earlier, the inhibitory efficiency account (Hasher & Zacks, 1988) emphasizes the role of inhibition in WM. Thus, according to this account whether proactive control or reactive control is better at explaining individual differences in WM depends on the particular function involved in these two types of control. If the binding-episodic inhibition account is correct, individuals' performance on reactive control should be correlated with performance on WM tasks since inhibition is involved in only the reactive control aspect of PI resolution. If the dual-inhibition account is true, the variance in proactive control and reactive control should both be correlated with the variance in WM since proactive control, reactive control and WM all involve inhibition. However, proactive control should have a higher correlation according to Braver's idea that proactive control is more sustained and requires more resource. Although this prediction is the same as the prediction made by the resource-limited controlled attention theory (that is, the variance in proactive control contributes more to variance in WM capacity), these two theories of WM can still be distinguished by examining whether performance on the binding tasks and on the inhibition tasks are directly correlated with WM capacity. The inhibitory efficiency account predicts that only performance on the inhibition tasks would be correlated with WM capacity. The resource-limited controlled attention theory predicts

that the inhibition tasks and the binding tasks rely on a general attention resource and performance on both types of tasks should be correlated with WM capacity. Furthermore, if the binding function or/and the inhibitory function could explain all the variance shared by PI resolution and WM, when controlling for these functions, PI resolution should not be correlated with WM.

Indeed, binding and episodic inhibition have both been considered as important components of WM capacity. As discussed in an earlier section, the role of inhibitory control in WM has been supported by Hasher and Zacks in studies on aging (1988; Hasher et al., 1999). In contrast, Oberauer (2005) argued for a relation between binding and WM, although an alternative explanation may apply (as discussed earlier). Oberaurer argued that his finding was consistent with the decline of the binding function in older adults which contributed to reduced WM capacity.

Besides binding and inhibition, other constructs often assumed to be important in WM are storage and processing. The storage and processing accounts of WM propose that individuals differ in WM in terms of the limited amount of information that can be maintained and processed simulatneously (Daneman & Carpenter, 1980; Engle, Cantor, & Carullo, 1992; Salthouse, 1990). That is, one WM resource is assumed to be allocated to both storage and processing. The greater the capacity required by processing across individuals (for instance, due to variations in expertise in the domain), the smaller the resource that remains for storage. In addition, Oberauer, Suβ, Wilhelm, and Wittmann (2008) reported a high correlation (r = .78) between performance on tasks that they argued tapped storage and processing (SP) and performance on binding tasks. Considering this high correlation, if binding has any unique contribution to PI and WM, this contribution should survive even when controlling for the variance that can be predicted by

storage and processing. Following the same logic, Oberauer et al. (2008) looked at the roles of storage and processing and the role of binding in reasoning. They found a significant correlation between the residuals of binding and reasoning after partialling out the storage and processing measure. Moreover, the residual correlation between binding and reasoning was as high as that between SP (storage and processing) and reasoning. Therefore, the present study also included measures of storage and processing, in order to investigate whether binding has a similar unique contribution to PI and WM beyond the role of storage and processing. However, measures of storage and processing (simple span tasks that involve item recall or recognition) inevitably involve PI resolution in addition to storage and processing. For example, in a task measuring storage and processing of phonological information – the rhyme probe task, participants are first presented with a list of auditory words. Then they are asked to determine whether a probe word rhymes with any of the words in the list. When a word in the preceding list rhymes with or contains the same phonemes as a negative probe, this negative probe is more difficult to be rejected. This difficulty is caused by PI and reduces participants' score on this task. Therefore, performance on these tasks also reflects the ability to resolve PI. Taking this into account, partialling out storage and processing may take away the variance shared by PI tasks and PI related functions (potentially inhibition or binding or both), and thus weaken the relationship between PI resolution and inhibition or between PI resolution and binding. Nevertheless, previous studies have also shown that the involvement of interference resolution in simple span tasks is less significant for young adults than old adults (Lustig, May, Hasher, 2001; May, Hasher, & Kane, 1999; Rowe, Hasher, & Turcottes, 2010). Since only young adults were tested in the proposed study, it is reasonable to assume that, even if the storage and processing measures do tap interference resolution to some degree, they do not take away a large amount of

variance related to interference resolution. Moreover, these storage and processing measures were designed to minimize the similarity of words both between and within lists, reducing the need for PI resolution.

Method

Participants

One hundred and forty-one young adults were tested in this study. One hundred and eleven participants were recruited from the Rice undergraduate student online experiment sign-up system, while the other thirty participants were recruited from the Houston metropolitan area. Participants from Rice University obtained four experiment participation credits, while participants from the Houston metropolitan area were compensated with $40. Their age ranged from 18 to 30. All participants had at lease a high school education. Informed consent was obtained from each subject in accordance with the guidelines and approval of the Rice University Institutional Review Board.

Materials and Procedure

Considering the lack of consensus on how to define and measure the constructs of interest, multiple measures were included for each construct. Thus, each latent variable reflected the common variance and cognitive processes among measures of each construct. Since at least three indicators are needed to identify a construct (Little, Lindenberger, & Nesselroade, 1999) in a multivariate space, at least three measures were included for each of the following contrasts: WM capacity, PI, binding, inhibition, and SP (storage and processing). All measures are summarized in Table 2.1.

All tasks except for the WM span tasks were administrated with the PsyScope software package (Cohen, MacWhinney, Flatt, & Provost, 1993). The WM span tasks were administrated

with E-prime software (Scheneider, Eschman & Zuccolotto, 2002). Tasks were administered over the course of two sessions, each lasting 1.5-2 hr and completed at least one week apart. All participants completed the WM tasks and the letter flanker negative priming task in the first session and the Stroop task and the tasks of storage and processing in the second session. Half of the participants completed the high proportion version of the PI tasks, the memory rhyme monitoring task and the local recognition task in the first session, while the other half completed the low proportion version, the non-memory rhyme monitoring task, and the saccade-antisaccade task in the second session. The PI tasks with the same proportion of interfering trials were administrated sequentially in the same session so that the proactive control or reactive control dominant strategy could sustain across tasks and thus were easier to detect.

Table 2.1

Summary of measures.

Constructs	Measures
WM	Operation span Reading span Symmetry span
PI	Word directed forgetting task (a high proportion version) Word directed forgetting task (a low proportion version) Word recent negatives task (a high proportion version) Word recent negatives task (a low proportion version) Pattern recent negatives task (a high proportion version) Pattern recent negatives task (a low proportion version)
Binding	Word local recognition task (memory task) Rhyme monitoring task (memory task) Rhyme monitoring task (non-memory task)
Inhibition	Stroop task Letter flanker negative priming task Saccade-antisaccade task
Storage and Processing	Category probe Rhyme probe Matrix span

Measures of WM capacity. Two verbal tasks and one spatial task were included as the measures to capture the common variance of WM capacity beyond any task-specific factors. All

three WM measures involve two tasks during encoding – one that emphasizes processing and one that emphasizes storage. Three trials of each set size (the number of items that need to be recalled in each trial) were tested. The score were the total number of trials that were correctly recalled in the order presented.

Operation span task (verbal WM). In a task developed by Unsworth, Heitz, Schrock, and Engle (2005), participants saw a math operation centered on a computer monitor. They were asked to solve the operation and recognize whether a displayed digit was the correct answer. As soon as the decision was made or the time limit (mean response time of the operation problem collected during practice plus 2.5 standard deviations) was over, they saw a letter that was also centered and asked to remember the letter. Each letter remained on the screen for 800 ms. The next screen was presented with a new operation followed by a letter. Following each complete set of operation–letter pairs, subjects were instructed to recall the letters in the order presented. The set sizes varied from three to seven and were randomized between sets. The procedure is illustrated in Figure 2.1.

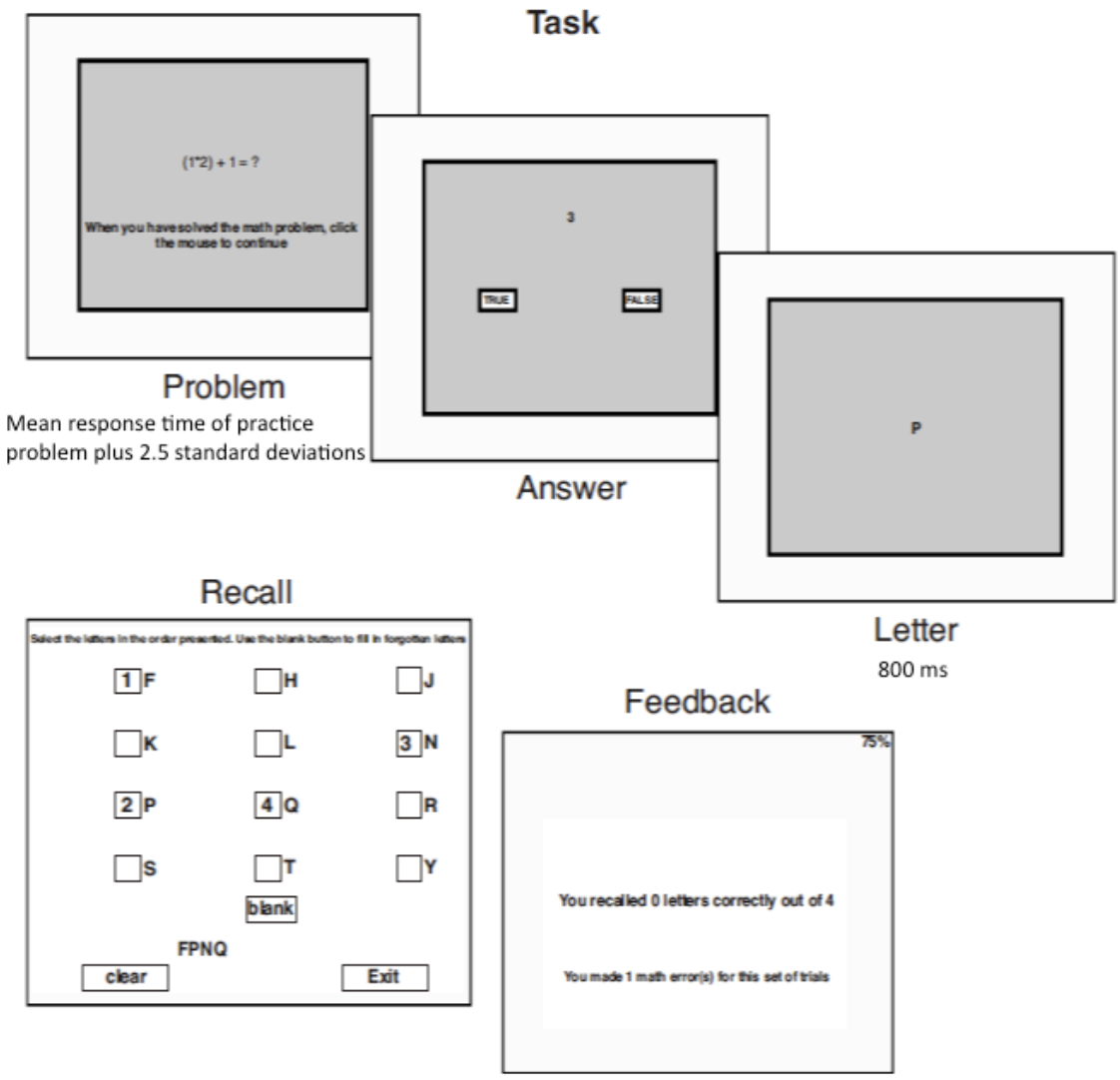

Figure 2.1: Illustration of the operation span task (adapted from Unsworth et al., 2005).

Reading span task (verbal WM). In a task modified from Kane et al. (2004), each display was composed of one understandable or nonsensical sentence. Similar to the operation span task, participants read the sentence and judged whether it "made sense", and then saw a to-be-remembered letter. Immediately after that, the next display appeared, and the same series of operations was required. The set sizes varied from two to five and randomized between sets. The same timing parameters used in the operation span task were used. The set sizes varied from three to seven and were randomized between sets.

Symmetry span task (spatial WM). In a task modified from Kane et al. (2004), the processing task was to determine whether an 8 by 8 matrix of filled and unfilled squares was symmetrical along its vertical axis. As soon as the response was made, a to-be-remembered 4 by 4 matrix pattern with ONE filled square appeared and stayed on the display for 650 ms. The task was to recall the 4 x 4 matrix patterns in the order presented. The set sizes varied from two to five and were randomized between sets. The same timing parameters used in the operation span task were used. The procedure is illustrated in Figure 2.2.

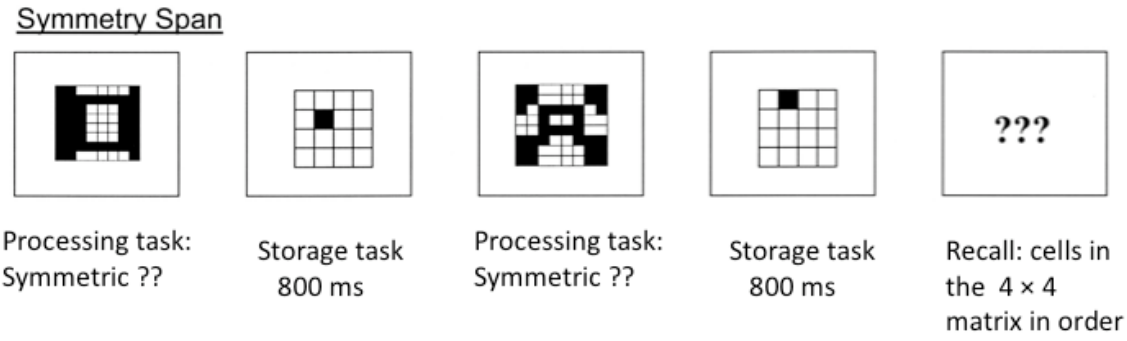

Figure 2.2: Illustration of the symmetry span task (adapted from Kane et al., 2004).

Measures of PI. Three PI tasks were conducted. For each of these two tasks, there were two versions – one with a majority of interfering trials (the high proportion version) and one with a low proportion of interfering trials (the low proportion version). These two versions were designed to measure proactive control and reactive control of PI resolution, respectively[3].

Word recent negatives task (verbal PI). This task has been mentioned repeatedly as a typical PI task. In this task, subjects were presented with a list of words and then asked to judge

[3] The pilot results of the first eight subjects in this study demonstrated a trend that these two versions of the PI tasks would indeed measure different types of PI resolution. Specifically, in the tasks with a high proportion of interfering trials, the PI effect (i.e., response times for the interfering trials minus response times for the control trials) was smaller than in the tasks with a low proportion of interfering trials (76 ms vs. 150 ms). Such a trend was consistent with the prediction that a proactive control mechanism that could prevent PI plays a bigger role in the high proportion version than in the low proportion version.

whether a probe appeared in the current list. The interfering trials were recent negative trials. Adapted from Badre and Wagner (2005), participants were asked to remember a list of four one to two-syllable words presented simultaneously around a display center for 2s. Then after a 2.5s blank screen, participants were asked to determine whether a probe (which stays on screen for 2.5s) was in the current list or not. Following the probe, a fixation stayed on the screen for 0.5s before the next trial started. Three types of probes were presented. Positive probes were those that appeared in the current but not preceding lists. Control negative probes were those did not appear in either the current or the preceding lists. The recent negative probes (also termed intrusion negative probes) consisted of words that were not members of the current list but appeared in the immediately preceding list. In the low proportion version, there were 20% interfering trials in the task (15 intrusion negatives, 25 control negatives, 35 positives). The high proportion version of this task included 67% interfering trials (50 intrusion negatives, 10 control negatives, 15 positives). The procedure is illustrated in Figure 2.3.

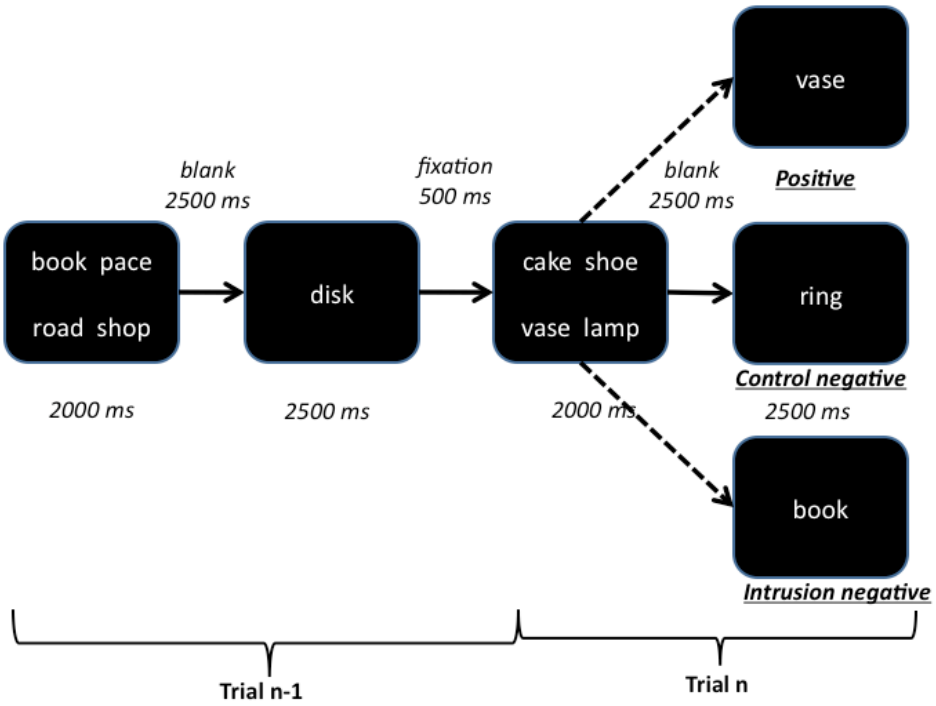

Figure 2.3: Illustration of the word recent negatives task.

Word directed forgetting task (verbal PI). This task was adapted from the modified version of the Sternberg recognition task by Oberauer (2005). Similar to the recent negatives task, a word list was presented, and then subjects were asked to judge whether a probe occurred in the current list. Different from the recent negatives task, however, the to-be-remember list consisted of two sub-lists defined by their ink colors (red or blue). The two sub-lists, each of which contained two one- or two-syllable English nouns, were presented on the same screen around a display center for 2 seconds. The two words in the same row or column were always written in the same ink color. However, the color of each row was randomized across trials, so that the color of words could not be inferred by its location on the screen. Importantly, a color cue (a colored frame) was presented centrally for 2 seconds after a 1s fixation following the presentation of the list to indicate the color of the sub-list that needs to be remembered. At this point, participants could either inhibit the irrelevant items (i.e., the sub-list in the un-cued color; as proposed by the item inhibition account) according to the cue, or ignore the cue and strengthen the item-context association for all items (as proposed by the binding account). The presentation of the cue was followed by a probe word in the cued color displayed in the frame for 2 seconds, and then a 500 ms fixation. Subjects were asked to judge whether the probe was a word in the cued sub-list. There were three probe types: positives, control negatives, and intrusion negatives. Positives were those that were members of the cued sub-list. Control negatives were novel words never occurring in any of the sub-lists. Intrusion negatives were interfering probes that were from the uncued sub-lists. In the low proportion version, there were 20% interfering trials in the task (15 recent negatives, 25 non-recent negatives, 35 positives). The high proportion version of this task included 67% interfering trials (50 recent negatives, 10 non-

recent negatives, 15 positives). The procedure is illustrated in Figure 2.4.

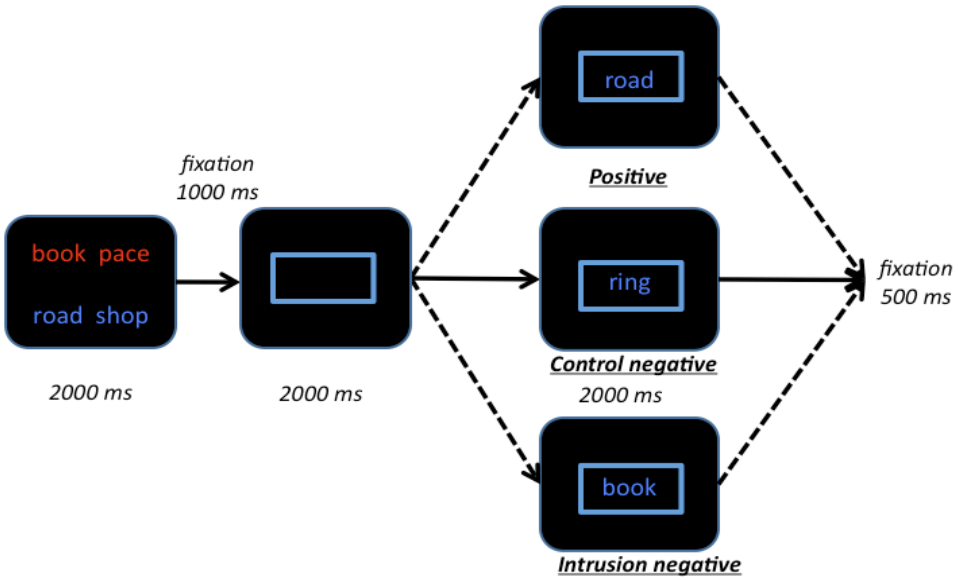

Figure 2.4: Illustration of the word directed forgetting task.

Pattern recent negatives task (verbal PI). This task was adapted from Badre and Wagner (2005). The procedure, design, and analysis were similar to the word recent negatives task except that 20 abstract visual patterns were used as stimuli. Moreover, only three patterns were presented simultaneously in each list for 2.5s. The delay (a fixation) between the list and the probe was 3s. The probes were presented for 2.5s after the fixation. In the low proportion version, there were 19% interfering trials in the task (15 intrusion negatives, 30 control negatives, 35 positives). The high proportion version of this task included 63% interfering trials (50 intrusion negatives, 15 control negatives, 15 positives). The procedure is illustrated in Figure 2.5.

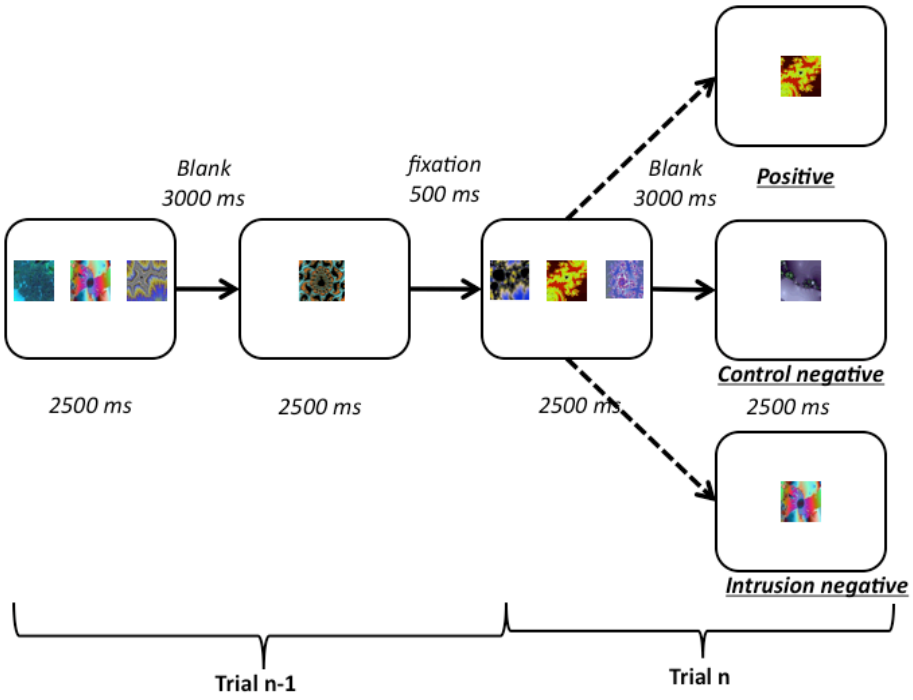

Figure 2.5: Illustration of the patter recent negatives task.

Measures of binding. Three tasks were used as measures of the binding function. All these tasks involved integration between item and context information.

Word local recognition task (memory binding). This task was modified from the study of Oberauer (2005). At the beginning of each trial, participants were asked to remember four one- to two-syllable words. Each word in the memory list was presented sequentially in one of four rectangular frames at each corner of the screen. Each of the word was presented for 0.5s. The order of locations where each word was presented was randomized cross trials. After a 2 second fixation screen following the presentation of the list, a probe appeared in one of the frames for 2.5s, and participants were instructed to identify whether the probe matched the word presented in that frame in the list. There were three types of trials. For positive trials, the probes matched the words in the list in the same frame. For intrusion negative trials, the probes were in the list but in a wrong frame. The intrusion negative trials were interfering trials. Control

negative trials presented probes that never occurred in the list. In this task, participants needed to remember the item-location associations for all items before the probe was presented. Location memory was more important for the intrusion negative trials than the control negative trials, since participants could easily reject the control negative trials due to the low level of item familiarity. Therefore, the strength of binding was measured by the accuracy difference between control negative and intrusion trials –with larger values indicating worse binding . Assuming that the binding process was involved in this task as a proactive control mechanism (i.e., involved before the probe is presented) and proactive control was more involved when the proportion of interfering trials is high, a high proportion of interfering trials was included (50 intrusion negatives, 10 control negatives, 15 positives). After a 500 ms fixation following the presentation of the probe, the next trial started. The procedure is illustrated in Figure 2.6.

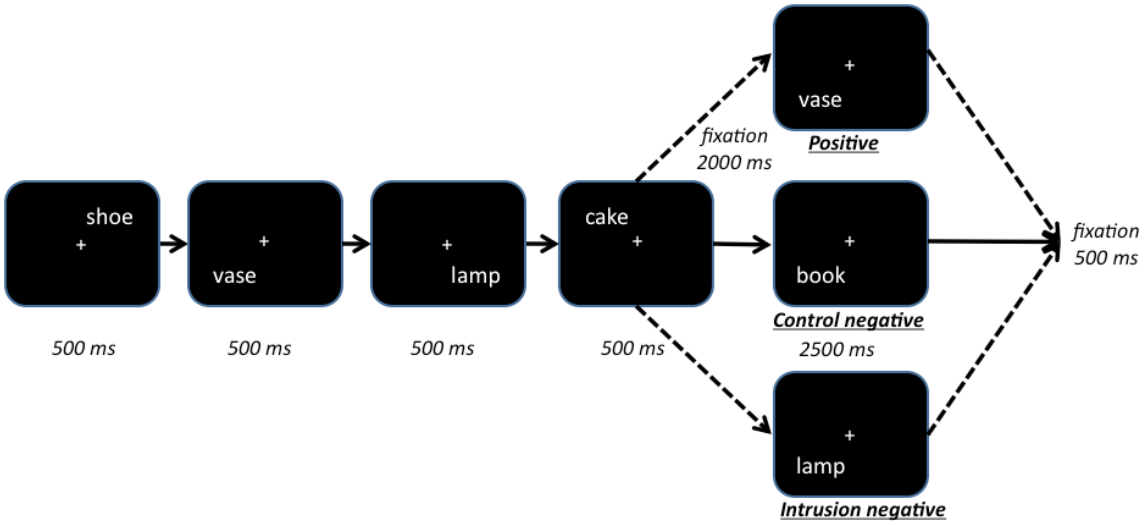

Figure 2.6: Illustration of the local recognition task.

Rhyme monitoring (memory binding). In a task modified from the study of Oberauer et al. (2008), participants saw one word in one of 5 cells arranged in a cross. Every word was presented for 2s at a randomly chosen cell and then removed. Immediately following the

disappearance of one word, the next word was presented in the same manner. Participants needed to remember the words last presented in each cell of the matrix. In addition, they needed to push a button whenever they found three words that rhymed in a row or a column. There were nineteen words presented sequentially in each trial. Performance was scored as the number of correct decisions across 15 trials. The total score was 45 (3 positive decisions required in each trial). This task measured the binding function because subjects needed to remember both the pronunciations and the positions of words to complete the task. The procedure is illustrated in Figure 2.7.

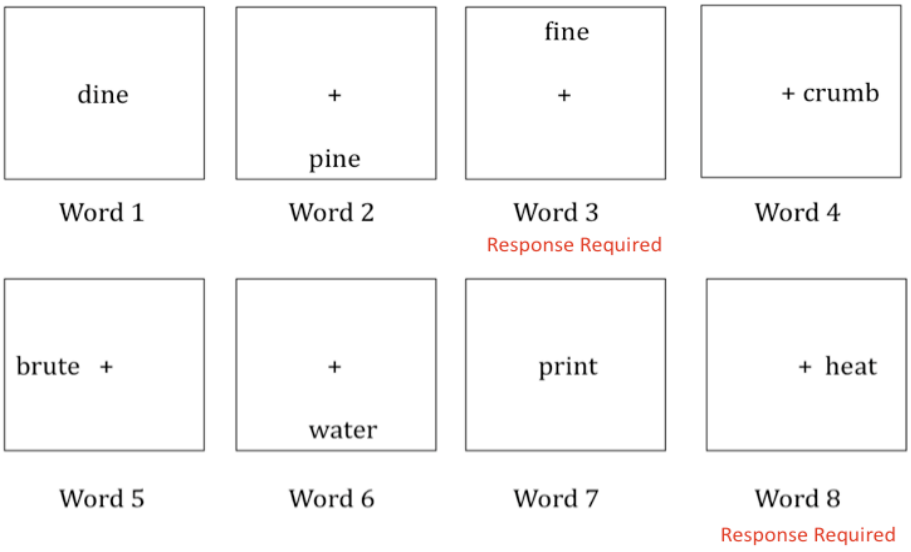

Figure 2.7: Illustration of the rhyme monitoring task (the memory version).

Rhyme monitoring (non-memory binding). This task was also modified from the study of Oberauer et al. (2008). It is a non-memory version of the rhyme monitoring task. Participants saw nine words at a time arranged in a 3 by 3 grid. Every 2s, one word at a random location in the grid was replaced by a new word. Participants needed to push a button whenever they found three words in that rhymed in a row or a column. There were fourteen replacements in each trial. No positive response was required on the first display before any replacement. Performance was

scored as the number of correct decisions across 15 trials. The total score was 45 (3 positive decisions required in each trial). The procedure is illustrated in Figure 2.8.

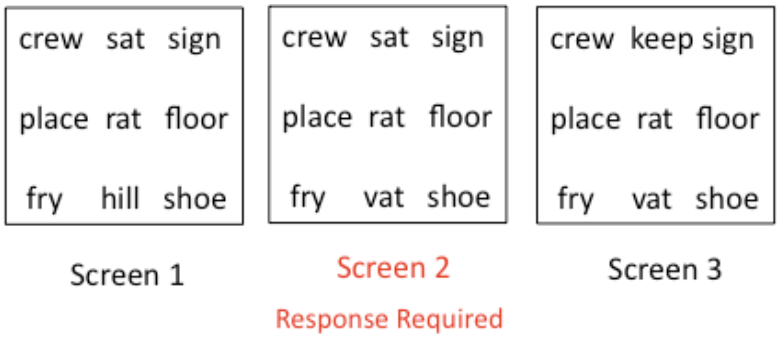

Figure 2.8: Illustration of the rhyme monitoring task (the non-memory version).

Measures of inhibition. Three tasks were included to measure individuals' inhibition ability.

Stroop task (verbal inhibition). This task was adapted from the study of Kane and Engle (2003). Each trial began with the presentation of a yellow READY? signal at the center of the screen against a black background. The ready signal remained on screen until the participant pressed a button on the button box, and was followed by a 600-ms blank screen. A centered, fixation signal then appeared for 500 ms, followed immediately by the target words or asterisks that remained in the center of the screen until the response. Subjects were asked to name aloud the color in which a letter string was presented on the screen, as quickly and accurately as possible. A voice-activated relay recorded response latencies to each letter string, reflecting the time from stimulus onset to response onset. To minimize a conflict between task goals, no congruent trials were included in the stimuli. Sixty-five trials were included as critical incongruent trials where the letter string is a color word (RED, BLUE, YELLOW or GREEN) that is written in different color ink. Another 77 neutral stimulus (asterisks in lengths matched the color words) presented in red, blue, yellow or green were also included. The inhibition effect

was the response times for incongruent trials minus those for neural trials.

Letter flanker negative priming task (verbal inhibition). The task used in Tse, Hutchison, and Li (2010) was also adopted as one of the verbal inhibition tasks. The stimuli were pairs of prime-probe displays, each consisting of a triplet of the letters A, B, C, and D (e.g., ABA). A 250 ms fixation started the trial, following by a 250 ms blank screen. Then the prime display was presented for 500 ms. A fixation point was then presented for 1s, followed by the probe display for 500 ms. At the end of each trial, another fixation point lasted for 1s before the next trial started. During the prime and probe displays, participants were asked to press keys that correspond to each target letter – the letter in the middle of each triplet, while ignoring the flanker letter – the letter on the ends of each triplet. For instance, a blue button on the response box corresponded to the letter A and a red button for the letter B. Two types of prime-probe pairs were included (48 trials each). For control pairs, none of the letters in the prime display repeated at any position in the probe display, while for negative priming pairs, the flanker letter in the prime display became the target in the probe display (e.g., ABA-CAC). According to the finding from the study of Tse et al. (2010), response times for the probe display of negative priming pairs should be longer than those for control pairs. Presumably, this effect reflects how much the flanker letters that become target letters in the probe display were inhibited in the prime display. For example, for a display pair ABA-CAC, because "A" was a flanker letter in the prime display, it needed to be inhibited to facilitate the responses to target letter "B". When the flanker letter "A" becomes the target in the probe display, subjects take longer time to reactivate them. The longer this reactivation process takes, the greater level of inhibition is assumed to be. Therefore, the inhibition function was measured using the response times for the probe displays in negative priming pairs minus those in control pairs. The trials in which responses to the prime displays

were incorrect were excluded from the analysis, since the incorrect responses may be an indicator of the failure of the inhibition of the flanker letter. In addition, the following situations never occurred: the prime flanker was the probe flanker (e.g., ABA-ACA), the prime target was the probe target (e.g., ABA-CBC), or the prime target was the probe flanker (e.g., ABA-BCB). To discourage a strategy of episodic retrieval, the colors and fonts of the stimuli were different between the prime and probe displays. The procedure is illustrated in Figure 2.9.

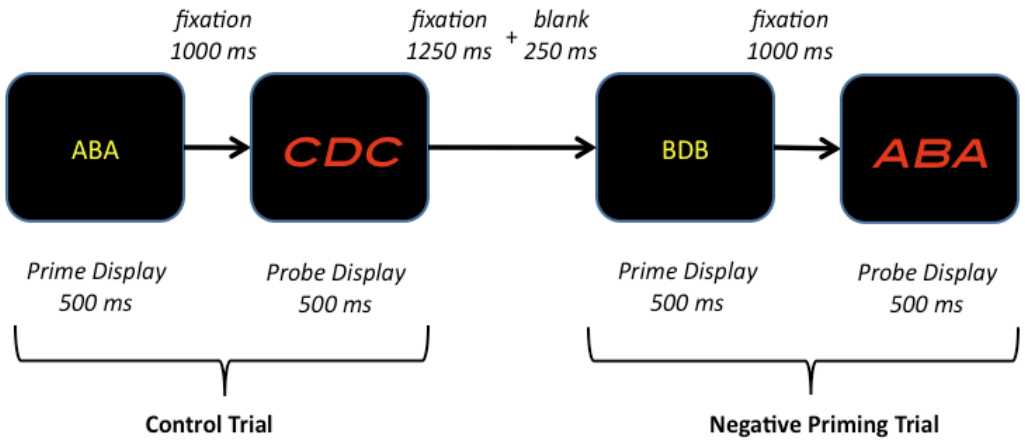

Figure 2.9: Illustration of the letter flanker negative priming task.

Saccade-antisaccade task (spatial inhibition). This task was modified from Kane et al. (2001). Two types of blocks were conducted. They were a prosaccade block and two antisaccade blocks. Each block consisted of 108 trials. Each trial began with a blank screen (500 ms) followed by a fixation at the center of the screen. The fixation remained on the screen until the participants press a button on the button box, which was then followed by a cue (a red filled square) that appeared for 175 ms to the right or left of fixation. Immediately following the cue, a target number appeared to the right or left of the fixation in the space. In the prosaccade block, the target number was presented on the same side as the cue. In the antisaccade block, the target was presented on the opposite side of the cue. The target on each trial was the number of "1", "2"

or “3”. The target was presented for 150 ms and then immediately followed by a mask (a filled square in the same size as the cue). Subjects were asked to identify the masked target stimulus on each trial and to press the key that corresponded to the target as quickly and accurately as possible. The mask would disappear immediately after participants made a response and the next trial would begin. Three buttons on the button box were labeled with colored stickers, 1, 2, and 3, respectively. The target number 1, 2, and 3 occurred an equal number of times. Because the cues draw subjects’ attention to the side opposite the targets, the tendency of attending to the cued location needed to be suppressed. The better someone can suppress this tendency, the better he/she would perform in this task. The inhibition effect was the difference in response accuracy between the prosaccade block and the antisaccade block. The procedure is illustrated in Figure 2.10.

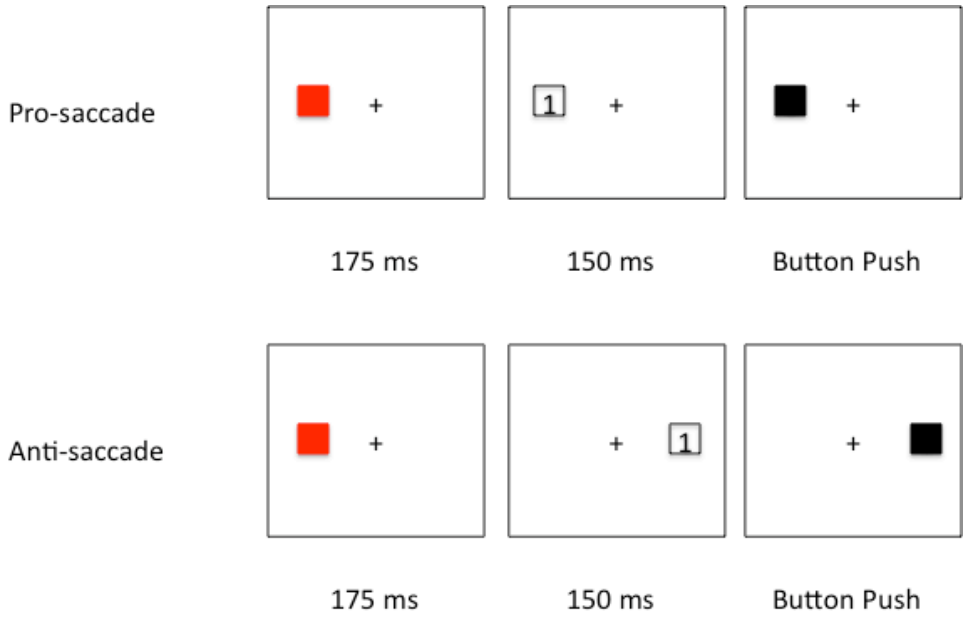

Figure 2.10: Illustration of the saccade-antisaccade task.

Measures of storage and processing. Three short-term memory (STM) tasks (two verbal and one spatial) were conducted to obtain the measures of storage and processing.

Category probe task (verbal storage and processing). Adapted from the study of Martin, Shelton, and Yaffee (1994), a list of words was presented auditorily for participants to remember. After a 1s delay following each list, a probe word was presented, and participants were asked to determine whether the probe was in the same category as any of the words in the list. The list length varied from four to six words. Twenty-four lists were tested at each length. Subjects were familiarized with the categories and category exemplars prior to the task. To minimize PI, the negative probe never appeared in the preceding list. In addition, the same word was not presented in consecutive lists. The dependent variable was average accuracy.

Digit span. Participants recalled sequences of digits (1-9) that were presented for 1s each, with a 500-ms blank between each digit. Set sizes ranges from 3 to nine. Two trials were tested for each set size. Digits appeared equally often. Experimenters recorded the number of trials in which the numbers were recalled correctly in order. The total score was 16.

Matrix span task (spatial storage and processing). In a task modified from Kane et al. (2004) study, participants were asked to recall the sequences of red-square locations within successive matrices. Each matrix was 4 by 4 (5 cm by 5 cm) in size and has one of the 16 squares in red. In addition, each matrix was presented for 650 ms with a 500-ms inter-stimulus blank screen. Set sizes ranged from 2 to 7 matrices. Three trials were tested for each set size. To minimize PI, matrices with any same filled location were not presented in consecutive lists. Participants filled in the locations and sequences of the filled cells on an answer sheet. The dependent variable was the total number of matrix in which the locations and sequences of the filled cells were recalled correctly. The total score was 18.

Results

Data Preprocessing

Data from seventeen participants were excluded from the analyses (eleven had average accuracy below 60% in at least one task, two were not native English speakers, one was color-blind, and three did not complete all tasks). Among these participants, three were from the community sample.

Reaction times and accuracies were trimmed before the analyses. Responses in the category span and two rhyme monitoring tasks that were under 200 ms were not counted (less than 0.9% of all observations). All accuracy data were arcsine transformed to improve normality for the confirmatory factor, regression, and correlation analyses.

For reaction times, extreme values that were shorter than 200 ms or longer than 2500 ms for most tasks (exceptions: 200-3000 ms for two pattern tasks, 200-1500 ms for the letter flanker task) were excluded (less than 0.1% of all observations). Then, values three standard deviations away from the subject mean in each task were replaced by the values of three standard deviations (less than 1.3% of all observations were replaced).

At the group level, except for the repeated measures ANOVA analyses, for both response times and accuracies, subject means that were three standard deviations away from the group mean for that variable were replaced by the value at three standard deviations (less than 0.9% observations were replaced).

After the trimming/transformation process, all variables achieved a satisfactory level of normality. In addition, reliability was good or acceptable in all tasks except for the letter flanker negative priming task and the high interference version of the pattern recent negatives task. See Table 2.2 for all descriptive statistics.

Table 2.2

Descriptive statistics.

Constructs	Tasks	Conditions	M	SD	Range	Skew	Kurtosis	Reliability[1]
PI *High Interference version* (Response Times)	Directed Forgetting	Control	795ms	189ms	460-1504ms	.92	1.28	.44[2]
		Intrusion	909ms	203ms	476-1444ms	.31	-.13	
	Word Recent Negative	Control	903ms	207ms	492-1544ms	.48	.17	.16[2]
		Intrusion	1022ms	228ms	586-1557ms	.10	-.78	
	Pattern Recent Negative	Control	957ms	194ms	585-1549ms	.60	.40	.39[2]
		Intrusion	1006ms	190 ms	641-1587ms	.60	.53	
PI *Low Interference version* (Response Times)	Directed Forgetting	Control	877ms	194ms	493-1423ms	.54	-.11	.52[2]
		Intrusion	986ms	239ms	524-1659ms	.54	-.11	
	Word Recent Negative	Control	895ms	192ms	557-1501ms	.89	.90	.35[2]
		Intrusion	1032ms	240 ms	635-1784ms	.90	.84	
	Pattern Recent Negative	Control	983ms	187ms	589-1551ms	1.00	1.17	.07[2]
		Intrusion	1026ms	218ms	516-1662ms	.74	.58	
PI *High Interference version* (Accuracy)	Directed Forgetting	Control	97%	7%	66-100%	-1.54[5]	2.35[5]	.52[3]
		Intrusion	95%	6%	72-100%	-.85[5]	.65[5]	
	Word Recent Negative	Control	98%	6%	74-100%	-1.27[5]	1.46[5]	.46[3]
		Intrusion	96%	5%	74-100%	-.51[5]	-.38[5]	
	Pattern Recent Negative	Control	89%	7%	67-100%	-.27[5]	.78[5]	.24[3]
		Intrusion	87%	8%	63-100%	-.23[5]	-.17[5]	
PI *Low Interference version* (Accuracy)	Directed Forgetting	Control	97%	5%	71-100%	-.84[5]	.64[5]	.48[3]
		Intrusion	94%	8%	65-100%	-.57[5]	-.40[5]	
	Word Recent Negative	Control	99%	3%	88-100%	-.82[5]	.21[5]	.39[3]
		Intrusion	96%	6%	76-100%	-.94[5]	.30[5]	
	Pattern Recent Negative	Control	87%	7%	61-97%	-1.03[5]	1.66[5]	.51[3]
		Intrusion	88%	12%	53-100%	-.06[5]	-.24[5]	
Binding	Local Recognition	Difference[6]	12%	12%	-18-49%	.08	.58	.79
	Memory – Rhyme Monitoring	Raw score	29	6	8-40	-.63	.94	.79
	Nonmemory – Rhyme Monitoring	Raw score	26	7	7-41	-.23	-.37	.94
Inhibition	Stroop	Difference[6]	-35 ms	280 ms	-35-280 ms	-.92	.99	.86
	Saccade-antisaccade	Difference[6]	15%	9%	0-44%	-.25	.01	.87
	Letter Flanker Negative Priming	Difference[6]	-61 ms	47 ms	-61-47 ms	-.48	.67	-.03
WM	Operation Span	Raw score	47	17	5-75	-.22	-.69	.80[4]
	Reading Span	Raw score	44	16	0-75	-.21	-.34	.78[4]
	Symmetry Span	Raw score	22	9	2-42	.04	-.27	.86[4]
SP	Digit Span	Raw score	12	2	7-16	-.14	-.75	.79[4]
	Category Span	Raw score	.82	.07	.62-.94	-.48	-.23	.69
	Matrix Span	Raw score	10	2	4-15	-.17	-.14	.86[4]

[1] Split-half reliability; [2] reliabilities for difference scores between the intrusion conditions and the control conditions; [3] reliabilities for regression residuals of the composite scores for the intrusion conditions on the composite scores for the control conditions; [4] from Kane et al., (2004); [5] statistics of composite scores of response times and accuracy; [6] difference score: interference condition - control condition

Effects of PI, binding and inhibition

Effect of PI. Reaction times and accuracy in the PI tasks were analyzed via a three-way ANOVA of Task (directed forgetting vs. word recent negative vs. pattern recent negative) × Probe Type (intrusion vs. control) × Proportion (high vs. low). See Figure 2.11 for the mean response times and accuracy.

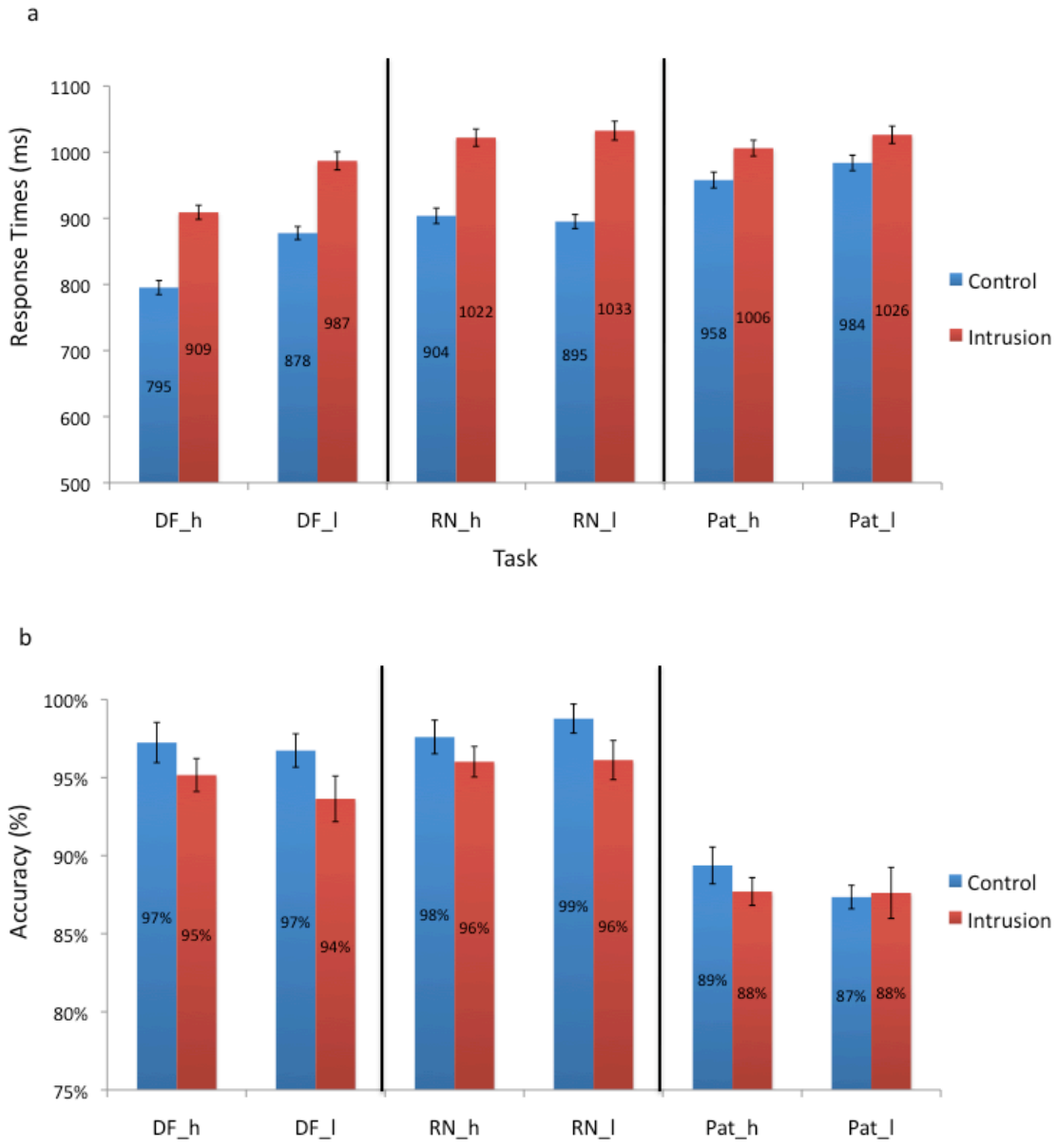

Figure 2.11: a) Response times. b) accuracy. "DF": the directed forgetting task; "RN": the word recent negative task; "Pat": the pattern recent negative task. "_h": the version with a high proportion of interference trials; "_l": the version with a low proportion of interference trials. Error bars represented standard errors corrected for between-subject variability.

For reaction times, participants took longer to respond to intrusion trials than control trials, $F(1, 123) = 410.86$, $p < .001$, $\eta^2_{partial} = .77$, and took longer to respond in the low interference proportion version tasks than the high proportion versions, $F(1, 123) = 6.11$, $p = .02$, $\eta^2_{partial} = .05$. The main effect of Proportion may be caused by a difference in response bias. In the high proportion versions, the proportions of negative trials were larger than those in the low proportion versions. Thus, they showed a larger response bias towards negative responses in the high proportion version tasks compared in the low proportion version tasks, $t = 3.26$, $p = .001$, $d = .29$, resulting in the faster response times for the negative trials in the high proportion version tasks. This *t*-test was conducted on the response bias measures calculated from a signal detection analysis (high proportion: $c = .21$; low proportion: $c = .04$). The main effect of Task was also significant, $F(2, 246) = 39.95$, $p < .001$, $\eta^2_{partial} = .25$. Tests of contrasts between tasks (Corrected by Bonferroni adjustment, $p < .016$ to be significant) found that participants responded faster in the directed forgetting task than the word recent negative task and the pattern recent negative task, $F(1, 123) = 45.48$, $p < .001$, $\eta^2_{partial} = .27$; $F(1, 123) = 69.91$, $p < .001$, $\eta^2_{partial} = .36$. Moreover, participants responded faster in the word recent negative task than the pattern recent negative task, $F(1, 123) = 6.14$, $p = .02$, $\eta^2_{partial} = .05$. There was no significant interaction between Probe Type and Proportion, $F(1, 123) = .16$, $p = .69$, $\eta^2_{partial} = .001$. This finding did not provide evidence for a smaller PI effect in the high proportion version in which proactive control was encouraged and presumably could reduce PI compared to the low proportion version. The interactions between Task and Proportion and between Task and Probe

Type, however, were significant, $F(2, 246) = 9.74$, $p < .001$, $\eta^2_{partial} = .07$; $F(2, 246) = 40.30$, $p < .001$, $\eta^2_{partial} = .25$, respectively. Therefore, a two-way ANOVA of Condition (intrusion vs. control) × Proportion (high vs. low) was conducted for each task. All three tasks showed a significant main effect of Probe Type (directed forgetting task: $F(1, 123) = 316.52$, $p < .001$, $\eta^2_{partial} = .72$; word recent negative task: $F(1, 123) = 259.18$, $p < .001$, $\eta^2_{partial} = .68$; pattern recent negative task: $F(2, 246) = 35.38$, $p < .001$, $\eta^2_{partial} = .22$). Moreover, the directed forgetting task showed a significant main effect of Proportion, $F(1, 123) = 22.99$, $p < .001$, $\eta^2_{partial} = .16$. Participants responded faster in the high proportion version than in the low proportion version. In the other two tasks, the proportion effect was not significant (word recent negative task: $F(1, 123) = .003$, $p = .96$, $\eta^2_{partial} < .001$; pattern recent negative task: $F(1, 123) = 1.82$, $p = .18$, $\eta^2_{partial} = .02$). There was no significant three-way interaction, $F(2, 246) = 1.55$, $p = .21$, $\eta^2_{partial} = .01$.

For accuracy, participants made more errors for the intrusion trials than for control trials, $F(1, 123) = 29.91$, $p < .001$, $\eta^2_{partial} = .20$. The main effect of Proportion was not significant, $F(1, 123) = 1.72$, $p = .19$, $\eta^2_{partial} = .01$. The main effect of task, again, was significant, $F(2, 246) = 218.62$, $p < .001$, $\eta^2_{partial} = .64$. Tests of contrasts between tasks showed that participants made more errors in the pattern recent negatives task compared to the directed forgetting task and the word recent negatives tasks, $F(1, 123) = 205.44$, $p < .001$, $\eta^2_{partial} = .63$; $F(1, 123) = 336.38$, $p < .001$, $\eta^2_{partial} = .73$, respectively. They also made more errors in the directed forgetting task than in the word recent negatives task, $F(1, 123) = 16.41$, $p < .001$, $\eta^2_{partial} = .12$, suggesting a speed-accuracy tradeoff, given that participants responded faster in the directed forgetting task than the word recent negatives task. Moreover, the interaction between proportion and probe type was not significant, $F(1, 123) = .01$, $p = .92$, $\eta^2_{partial} < .001$, consistent with the results for response times

for which no difference of the PI effect sizes between the high proportion and low proportion versions was detected. In addition, the interactions between Task and Probe Type and the three-way interaction were both significant, $F(2, 246) = 3.66$, $p = .03$, $\eta^2_{partial} = .03$; $F(2, 246) = 3.89$, $p = .02$, $\eta^2_{partial} = .03$, respectively, although the interaction between task and proportion was not significant, $F(2, 246) = 3.00$, $p = .06$, $\eta^2_{partial} = .02$. Then, a two-way ANOVA of Probe Type (intrusion vs. control) × Proportion (high vs. low) was conducted for each task to examine the significant interaction effects. In the directed forgetting task and the word recent negatives task, the proactive interference effects were significant, $F(1, 123) = 15.61$, $p < .001$, $\eta^2_{partial} = .11$; $F(1, 123) = 33.09$, $p < .001$, $\eta^2_{partial} = .03$, respectively. That is, participants were less accurate for the intrusion negative trials than the control negative trials. In the pattern recent negative task, however, there was no effect of probe type, $F(1, 123) = 1.70$, $p = .19$. None of the interaction effects between proportion and probe type was significant in any task (directed forgetting task: $F(1, 123) = 1.50$, $p = .22$, $\eta^2 = .001$; word recent negative task: $F(1, 123) = 2.66$, $p = .11$, $\eta^2_{partial} = .002$; pattern recent negative task: $F(1, 123) = 2.97$, $p = .09$, $\eta^2_{partial} = .02$).

In summary, participants performed better in the directed forgetting task and the word recent negatives task compared to the pattern recent negatives tasks. These effects may be due to the fact that non-verbal materials (e.g., patterns) are more difficult to rehearse compared to verbal materials, which led to difficulty in the pattern task. Importantly, the PI effect (i.e., the effect of Probe Type) was significant in response times and accuracy of all tasks, except for the accuracy of the pattern recent negatives task. However, participants did not exhibit a significantly smaller PI effect in the high proportion tasks than the low proportion tasks. This finding failed to provide evidence for the assumption that the high proportion tasks would engage more proactive control that could reduce the PI effect.

Effect of binding in the local recognition task. Paired *t*-tests showed that participants made more errors and responded more slowly for the intrusion negative trials compared to the control negative trials, $t(123) = 11.11$, $p < 0.001$, 87% vs. 99% ; $t(123) = 26.59$, $p < 0.001$, 1246 ms vs. 912 ms, respectively.

Effects of Inhibition. Paired *t*-tests showed that participants made more errors and responded more slowly for the interference condition compared to the control condition in all three inhibition tasks (i.e., Stroop, saccade – antisaccade, letter flanker negative priming), except that accuracy was not analyzed for the Stroop task since a large proportion of errors were due to task-unrelated vocal responses. See Table 2.3 for the statistical results.

Table 2.3

Statistics for the effects of inhibition.

Tasks	Dependent Variables	*t* (123)	Mean (interference) vs. Mean (control)
Stroop	Response Times	24.59**	823 ms vs. 704 ms
Saccade - santisaccade	Response Times	23.16**	614 ms vs. 482 ms
	Accuracy	19.58**	82% vs. 98%
Flanker negative priming	Response Times	6.68**	639 ms vs. 614 ms
	Accuracy	2.78*	93% vs. 94%

** $p < .01$; * $p < .05$

Confirmatory Factor Analyses and Regression

In this section, all scores were transformed so that a higher score represented better performance. Therefore, a positive coefficient indicates a positive correlation between variables.

WM factor. Since scores on three measures of WM (operation span, reading span and symmetry span) were highly correlated (see Appendix), a latent factor of WM was extracted from the three tasks. Individuals' factor score was used in further analyses. The variance of each

task that can be explained by the common factor is 72% for the operation span task, 66% for the reading span task, and 46% for the symmetry span task.

Storage and Processing. The three measures of storage and processing did not significantly correlate with each other (see Appendix). These results failed to provide evidence for a common factor of storage and processing. Therefore, scores of each individual measure were used in further analyses to control for the contribution of storage and processing.

Binding and Inhibition. Individuals' performance on measures of binding and on measures of inhibition were examined first to determine whether binding and inhibition were separate factors. Only if distinct factors of binding and inhibition were identified would it would be meaningful to investigate the role of each factor in PI resolution and WM.

Dissociation between binding and inhibition. Two sets of confirmatory factor analyses were conducted to test whether binding and inhibition are separate constructs. The one-factor model assumed that measures of binding and inhibition are tapping the same cognitive ability, while the two-factor model assumed that there are separate binding and inhibition constructs.

Binding variables included in the confirmatory factor analyses were the difference in accuracies between the intrusion negative and control negative trials in the local recognition task and scores in the memory and no-memory versions of the rhyme monitoring tasks (calculated by hit rates minus false alarm rates). Inhibition variables were differences in reaction times between the interference condition and the control condition in the letter flanker negative priming task and the Stroop task and differences in accuracies between the saccade and antisaccade blocks in the saccade-antisaccade task.

The one-factor model produced a good model fit, $x^2(9) = 7.02$, $p = .64$, $CFI = 1.00$, $RMSEA = .00$, $SRMR = .04$. The factor loadings of all binding measures were significant, p

<0.01. The factor loading of the saccade-antisaccade task was also significant, $p = 0.01$. The factor loadings of the other two inhibition variables, however, were not significant (the Stroop task, $p = .06$; the letter flanker negative priming task, $p = .60$). The two-factor model also produced a good fit, $x^2(8) = 6.99$, $p = .54$, *CFI*= 1.00, *RMSEA* = .00, *SRMR* = .04. But again, factor loadings of measures on the inhibition factor were not significant for the Stroop and the letter flanker negative priming task, $p = .08$ and $p = .61$ respectively. The insignificant factor loadings for two inhibition variables in both models showed that this study failed to identify a common factor of inhibition among the three inhibition measures, and thus there was no need to compare the two models. This finding is also consistent with the low correlations between the three inhibition measures (see Appendix). Scores on the saccade-antisaccade task, the letter flanker negative priming task and the Stroop task were therefore used individually in further analyses as indicators of inhibition.

Interestingly, however, the saccade-antisaccade task loaded significantly on the same factor as three binding tasks, although the unexplained variance in the saccade-antisaccade task is higher compared to the tasks of binding (saccade-antisaccade: 90%, local recognition: 78%, non-memory rhyme monitoring: 54%, memory rhyme monitoring: 47%). One possible reason the saccade-antisaccade task but not the other measures of inhibition significantly loaded on the factor of binding is that both the saccade-antisaccade task and the tasks of binding involved spatial processing. In the saccade-antisaccade task, participants had to ignore spatial cues. In the tasks of binding, participants had to either remember (in the local recognition task) or make judgments (in the rhyme monitoring tasks; e.g., whether there were three rhymed words in a row) on locations of words. Besides the spatial processing involved in all four tasks, the saccade-antisaccade task may still involve an inhibitory process that was not engaged in the tasks of

binding. In contrast, the tasks of binding may still involve a binding process that is not required in the saccade-antisaccade task. Unfortunately, since the three tasks of inhibition did not significantly load on a common factor, I cannot examine the dissociation between the saccade-antisaccade task and the factor of binding via confirmatory factor analyses.

In further analyses of relations between binding/inhibition and PI and of relations between binding/inhibition and WM, the three binding tasks were treated as a separate construct from the saccade-antisaccade task and from the other two inhibition. A latent factor was extracted from the three measures of binding and the factor score was used as the variable of binding. The variances of each task that can be explained by the common factor are 47% for the local recognition task, 71% for the non-memory rhyme monitoring task, and 59% for the memory rhyme monitoring task. In contrast, the score on the saccade-antisaccade task was used as the third indicator of inhibition in addition to the scores on the Stroop task and the letter flanker negative priming task. If the saccade-antisaccade task does not involve a unique inhibitory function, it would not show a unique contribute to predicting the variance of PI or WM when the factor of binding is controlled.

Binding and Inhibition in WM. The factor score extracted from the three WM measures was used as the WM variable. A regression of the WM factor on the binding factor, scores on each measure of inhibition, and scores on each measure of storage and processing was conducted. All independent variable were entered simultaneously into the regression. A significant proportion of variance in WM was explained, $R^2 = .31$, $F(2, 121) = 7.30$, $p < .001$. The binding factor ($\beta = .23$, $t(123) = 2.49$, $p = .01$), the scores on the saccade-antisaccade task ($\beta = .18$, $t(123) = 2.15$, $p = .03$), and digit span ($\beta = .30$, $t(123) = 3.75$, $p < .001$) significantly predicted individuals' performance on WM tasks (see Table 2.4 for coefficients of the

independent variables; see Figure 2.12 for the scatter plot). The unique contribution of performance on the saccade-antisaccade task suggests that an inhibitory function that is distinct from the binding function is indeed involved in this task.

Table 2.4

Coefficients for predictor variables in the WM regression analysis (predictor variables: binding, inhibition, storage and processing).

DV: WM factor		*β*
Binding	Binding factor	.23*
Inhibition	Stroop	.03
	Anti-saccade	.18*
	Flanker	.05
Storage and Processing	Digit span	.30**
	Category span	.08
	Matrix span	.13

*$p < .05$; **$p < .01$

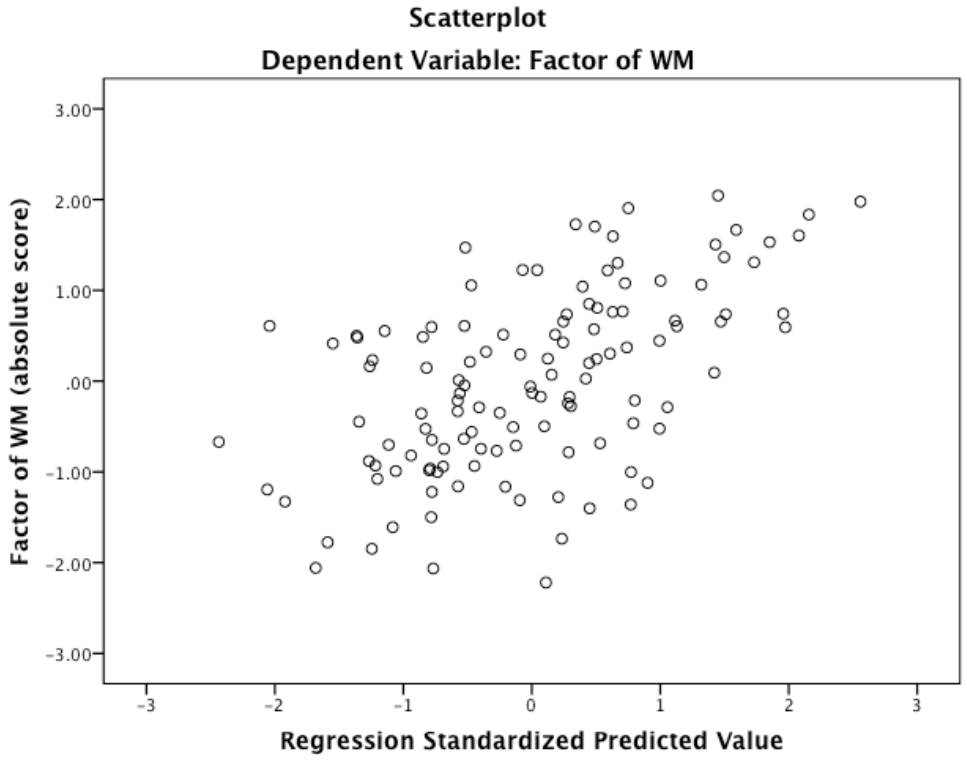

Figure 2.12. Scatter plot of WM on standardized predicted values (predictor variables: binding, inhibition,

storage and processing).

PI measures. The first question on PI measures is whether there are separate proactive control and reactive control mechanisms. Then, the second question is which function – the binding function or the inhibitory function - is involved in PI resolution. Since participants' data showed evidence of speed-accuracy tradeoffs, composite scores of accuracies and response times were analyzed. The composite scores were computed for each condition (i.e., control negative vs. intrusion negative) in each version (high vs. low proportion) of each PI task by averaging the *Z*-scores of the inverse of response times and arcsine-transformed accuracies. In order to determine the proactive interference effect, the composite scores for the intrusion negative condition were regressed on the control negative condition for each PI task, and the residuals[4] were used in the factor analyses. The residuals would reflect the portion of variance in the intrusion negative scores that could not be accounted for by baseline performance in the control condition.

No Dissociation between Proactive and Reactive Control. Two sets of confirmatory factor analyses were conducted to test whether there were distinct proactive control and reactive control factors. The one-factor models assumed that all PI measures load on one single PI factor, while the two-factor models assumed that measures of the high proportion version tasks and the low proportion version tasks load on separate PI factors. The PI tasks with the low proportion interfering trials should mainly measure reactive control. In contrast, the PI tasks with the high proportion interfering trials should mainly measure proactive control. Since significant interference effects were still observed, reactive control had to be engaged to resolve the

[4] Difference scores between performance in the intrusion conditions and the control conditions were not used in the analyses of PI resolution because of their low reliabilities. When the difference scores were used for the confirmatory factor analyses, none of the factor loadings was significant.

interference that arose. The one-factor model produced a good fit, $x^2(9) = 7.69$, $p = .57$, *CFI*= 1.00, *RMSEA* < .01, *SRMR* = .05, AIC = 2099.49. In addition, all factor loadings were significant, $p < .05$, except for those of the two versions of the pattern recent negatives tasks (high version: $p = .07$; low version: $p = .99$). The two-factor model also had a good fit, $x^2(8) = 6.88$, $p = 0.55$, *CFI*= 1.00, *RMSEA* < 0.01, *SRMR* = 0.04, AIC = 2095.04. Again, all factor loadings were significant, $p < .05$, except for those of the two versions of the pattern recent negatives tasks (high version on the factor of proactive control: $p = .08$; low version on the factor of reactive control: $p = .88$). The test of difference in model fits failed to provide evidence that the two-factor model fit the data better than the one-factor model, $x^2_{diff}(1) = .81$, $p = .37$; $AIC_{diff} = .81$, $p = .11$. Such a finding is consistent with the assumption of a common PI factor rather than distinct PI control mechanisms.

Thus, a common factor of PI resolution was extracted from the residuals of the composite scores for the intrusion conditions in all PI tasks (including the low and the high versions) when those scores were regressed on the composite scores for the control conditions (see Table 2.5 for the factor loadings).

Table 2.5

Variance of each PI task (composite scores) explained by the common factor.

Task	High proportion of interfering trials	Low proportion of interfering trials
Directed forgetting	78%	56%
Word recent negative	64%	58%
Pattern recent negative	34%	10%

Binding and Inhibition in PI. The factor scores for PI resolution were used in the analyses as the binding variable. Difference scores between interference and control conditions in each individual inhibition measures were used as inhibition variables. Scores in each storage and processing (SP) task were also included as control variables. All predictors were entered simultaneously into the regression.

Performance on category span and binding significantly predicted performance on PI resolution (category span: β = .22, $t(123) = 2.58$, $p = .01$; binding: $\beta = .35$, $t(123) = 3.88$, $p < .001$). In addition, performance on the saccade-antisaccade task showed a small contribution although the contribution was not significant, $\beta = .14$, $t(123) = 1.74$, $p = .09$. These variables explained a significant proportion of the variance in the dependent variable, $R^2 = .31$, $F(7, 116) = 7.52$, $p < .001$. The beta values of all variables are listed in Table 2.6. See Figure 2.13 for the scatter plot.

Table 2.6

Coefficients for predictor variables in the PI resolution regression analyses (including the outlier).

DV: PI resolution (residuals of composite scores for the intrusion condition regressed on the control condition)		β
Binding	Binding factor	.35**
Inhibition	Stroop	.05
	Anti-saccade	.14
	Flanker	.07
Storage and Processing	Digit span	-.01
	Category span	.23*

	Matrix span	.01

*$p < .05$; **$p < .01$

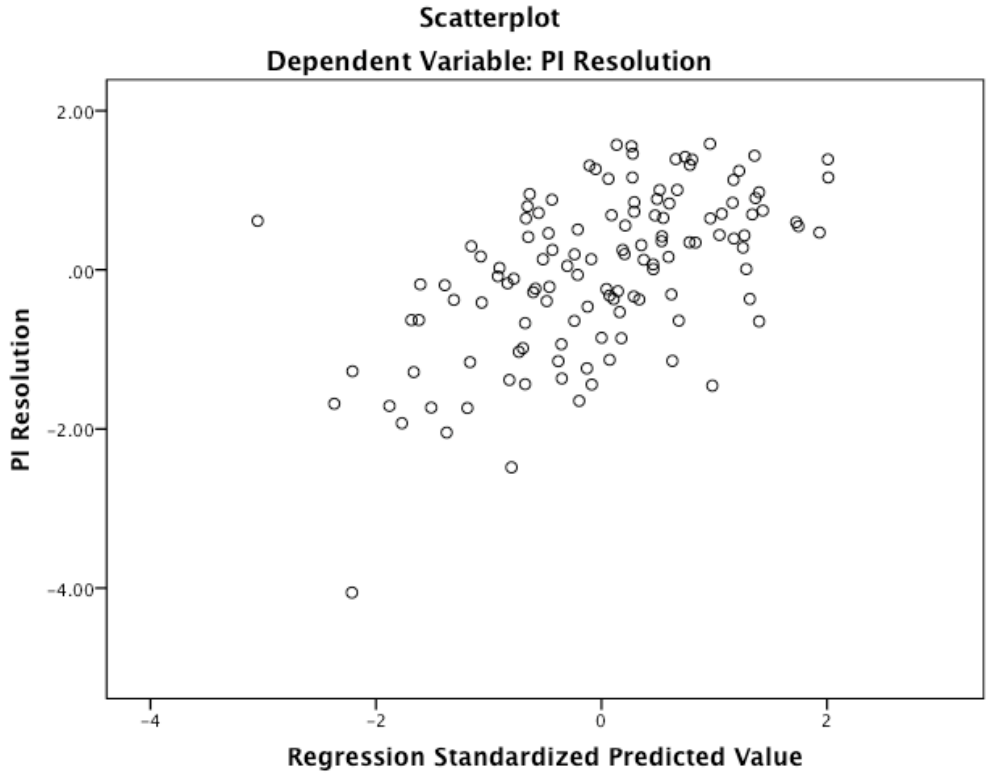

Figure 2.13. Scatter plot of PI resolution on standardized predicted values (including the outlier).

As shown in the scatter plot, one observation with the predicted value of -3.05 is an outlier. When excluding this observation in the same analysis, performance on category span, binding, and inhibition measured in the saccade-antisaccade task significantly predicted performance on PI resolution (category span: $\beta = .24$, $t(122) = 2.91$, $p = .004$; binding: $\beta = .39$, $t(122) = 4.50$, $p < .001$; saccade-antisaccade: $\beta = .18$, $t(122) = 2.31$, $p = .02$). These variables explained a significant proportion of variance in the dependent variable, $R^2 = .36$, $F(7, 116) = 9.30$, $p < .001$. The beta values of all variables are listed in the Table 2.7. The scatter plot is presented in Figure 2.14. These results showed that when controlling for storage and processing,

binding predicted of the size of the PI resolution effect beyond the variance predicted by inhibition. In addition, inhibition ability as measured in the saccade-antisaccade task predicted of the size of the PI resolution effect beyond the variance predicted by the binding ability. Such findings indicate that binding and inhibition measured in the saccade-antisaccade task are indeed dissociable abilities.

Table 2.7

Coefficients of predictor variables in the PI resolution regression analysis (excluding the outlier).

DV: PI resolution (residuals of composite scores for the intrusion condition regressed on the control condition)		*β*
Binding	Binding factor	.39**
Inhibition	Stroop	.02
	Anti-saccade	.18*
	Flanker	.05
Storage and Processing	Digit span	-.05
	Category span	.24*
	Matrix span	.03

*$p < .05$; **$p < .01$

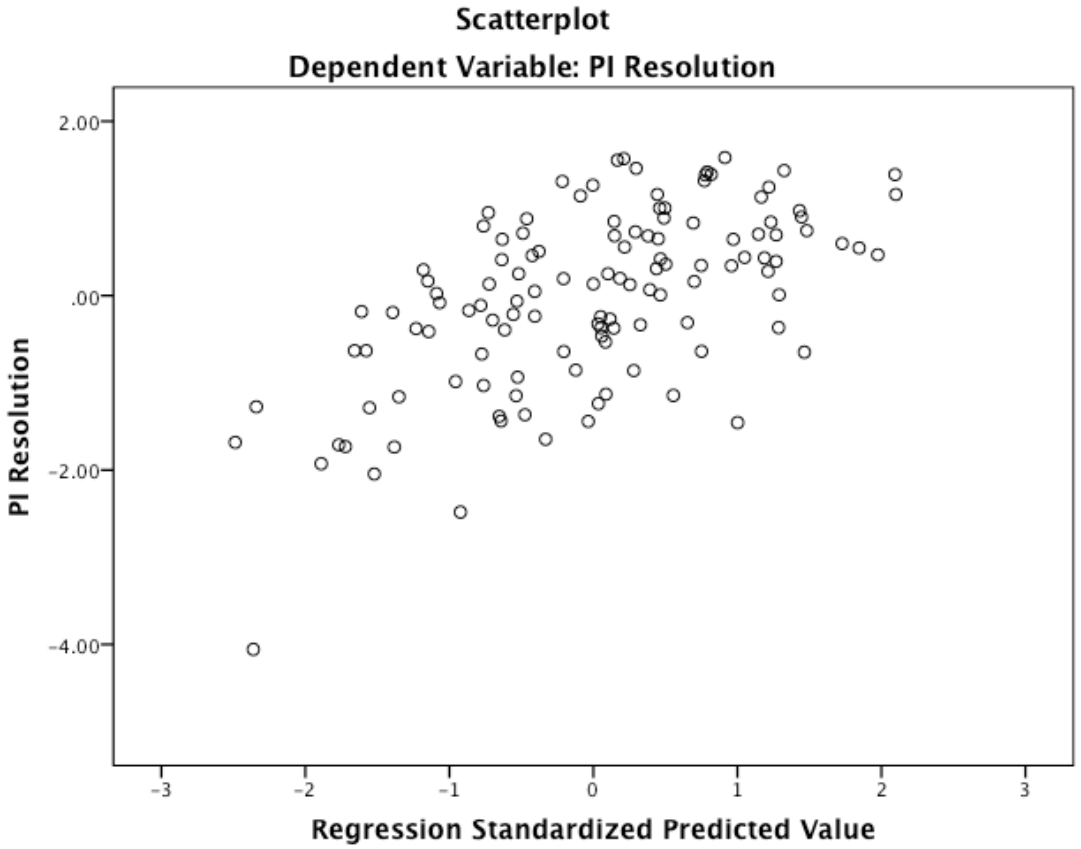

Figure 2.14. Scatter plot of PI resolution on standardized predicted values (excluding the outlier).

The Relation between PI and WM. A regression analysis was conducted using the PI resolution factor score to predict WM. The results showed that performance on PI resolution significantly predicted WM capacity, $\beta = .23$, $t(123) = 2.60$, $p = .01$, $R^2 = .05$. See Figure 2.15 for the scatter plot. The significance level did not change when excluding the outlier observation with the predicted value of -4.06.

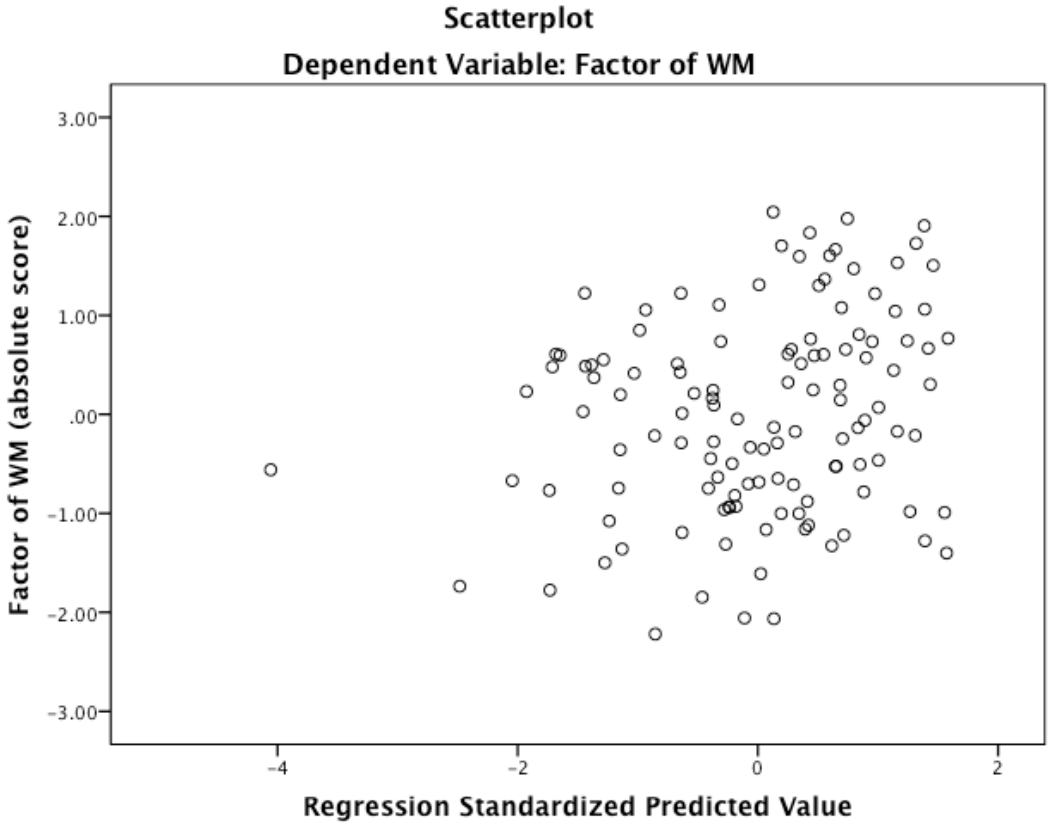

Figure 2.15. Scatter plot of WM on standardized predicted values (predictor variable: PI resolution).

Since individuals' performance on the binding factor and the saccade-antisaccade task was correlated with both PI resolution and WM, the commonly involved processes of binding and inhibition may be the reason why PI resolution is correlated with WM capacity. To examine this idea, the binding factor score and performance on the saccade-antisaccade task were included as predictors in addition to performance on PI resolution in a new regression. Moreover, digit span was also included as a predictor to control for storage and processing (this is the only measure of storage and processing that significantly predicted variance in WM based on the results of the previous regression of WM on binding, inhibition and storage and processing). All predictors were entered using the stepwise method. The results showed that the binding factor, digit span and performance on the saccade-antisaccade task significantly predicted WM capacity (binding

facctor: β = .28, $t(123) = 3.45$, p = .001; digit span: β = .33, $t(123) = 4.22$, $p < .001$; saccade-antisaccade task : β = .18, $t(123) = 2.16$, p = .03). A significant proportion of variance in WM was explained, R^2 = .28, $F(3, 120) = 15.73$, $p < .001$. In contrast, performance on PI resolution did not significantly predict variance in WM capacity with these other variables in the equation. See Figure 2.16 for the scatter plot.

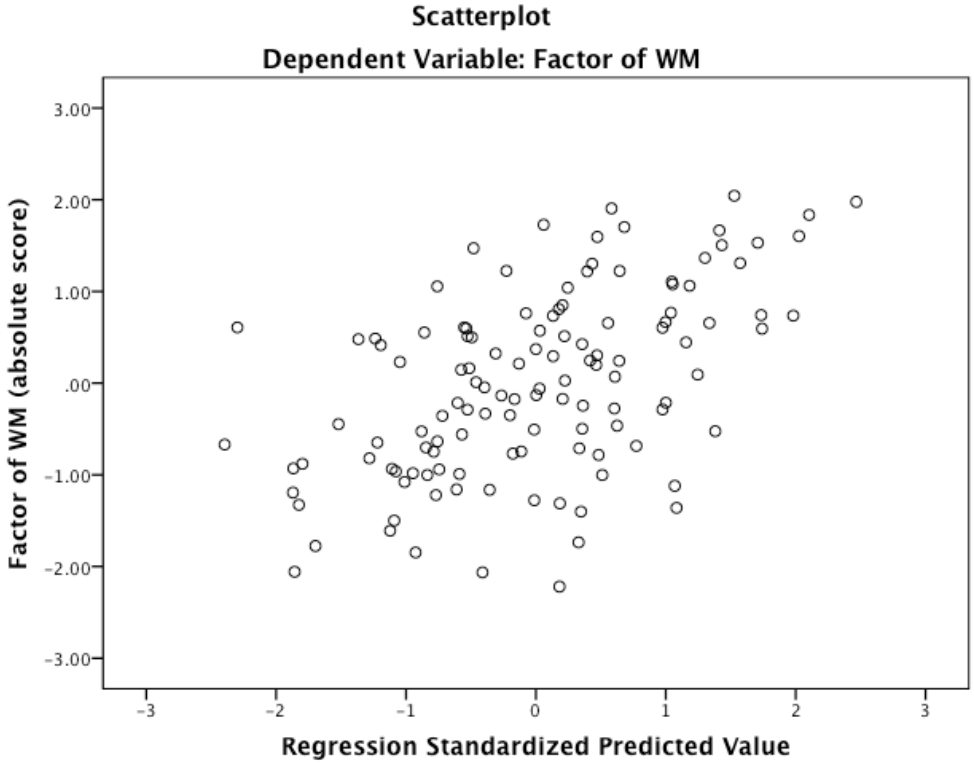

Figure 2.16. Scatter plot of WM on standardized predicted values (predictor variables: binding, inhibition, storage and processing).

Discussion

In this study, individual differences in binding, inhibition, PI resolution and WM were examined. Confirmatory factor analyses were conducted to test the dissociation between binding and inhibition ability as well as the dissociation between proactive control and reactive control in PI resolution. Linear regression analyses were conducted to examine the contribution of binding

and inhibition to PI resolution. The study also examined whether the binding and inhibitory functions involved in PI resolution underlie the close relationship between PI resolution and WM.

Dissociation between Inhibition and Binding

Two series of confirmatory factor analyses were conducted on measures of inhibition and binding: a model consisting of a single factor and a model consisting of two factors extracted from inhibition and binding measures respectively. Although the three binding indicators loaded on a common factor in both models, the three inhibition indicators did not significantly load onto a common factor in either model. The findings on inhibition measures failed to provide evidence for a common inhibitory process involved in the three inhibition tasks. This result is inconsistent with findings of previous studies that have identified a latent inhibition factor (Miyake et al., 2000; Friedman et al., 2008; Friedman & Miyake, 2004). Several reasons may potentially explain this discrepancy. First, the letter flanker negative priming task used in this study has not been used in any previous study. It turned out that the size and range of the inhibition effect in this task was quite small (effect size: 25ms; range: -67-47ms). Moreover, the reliability of this task was very low (see Table 3.2). The lack of variance and reliability perhaps caused its low correlation with other variables. However, a small degree of variance and low reliability could not explain why the other two inhibition tasks did not load on the same factor either. The range of performance on these two inhibition tasks were much larger (Stroop: -35-280 ms; Saccade-antisaccade: 0-44%), and the reliabilities were quite high (see Table 3.2). In addition, these two tasks were also used in previous studies by Miyake and colleagues who reported a latent inhibition factor. So why did not these two measure load on a common factor? One explanation is that these two tasks involve different types of inhibition. That is, the saccade-antisaccade task involves inhibition of spatial information, while the Stroop task involves inhibition of verbal

materials. Hamilton & Martin (2005) reported a patient who exhibited abnormally large interference effect in the Stroop task but not in the saccade-antisaccade task, indicating that the inhibitory functions involved in these two tasks are dissociable and engage different neural bases. This dissociation has also been supported by neuroimaging studies that reported left inferior frontal activation for inhibition of verbal materials but right inferior frontal activation for inhibition of motor responses or spatial information (Kan & Thompson-Schill, 2004; Aron, 2004). Moreover, consistent with the findings of the present study, an individual differences study on older adults also failed to identify a latent factor common to these two tasks (Hull, Martin, Beier, Lane, & Hamilton, 2008). To explain why Miyake and colleagues did find a common factor, it is worthy noticing a difference in the task design between their studies and those not reporting a common factor, including the present study. That is, performance on a prosaccade task was controlled in studies that failed to find a common factor of inhibition, whereas Miyake and colleagues only conducted the antisaccade task. Without controlling for performance on the prosaccade task, performance on the antisaccade task may reflect more general ability, such as general processing speed that might increase the correlation between the antisaccade task and other tasks.

The finding that only the saccade-antisaccade task loaded on the same factor with the three binding tasks in the one-factor model, suggesting that these tasks share some common processes. One possible reason the saccade-antisaccade task but not the other measures of inhibition loaded on the factor of binding is that both the saccade-antisaccade task and the binding tasks involved spatial processing. In the saccade-antisaccade task, participants had to ignore spatial cues. In the binding tasks, participants had to either remember or make judgments on locations of words. However, besides the spatial processing involved in all these tasks, the

saccade-antisaccade task may still involve an inhibitory process that was not engaged in the binding tasks. Moreover, it is possible, that the binding tasks may still involve a binding process that is not required in the saccade-antisaccade task. Unfortunately, this dissociation cannot be tested via confirmatory factor analyses since the three inhibition measures did not significantly load on a common factor. The method used in this study to test the dissociation between the binding tasks and the inhibition tasks is to treat the saccade-antisaccade task as a separate variable from the latent variable of binding constructed on the three binding tasks. If the saccade-antisaccade task significantly accounts for variance in PI resolution or WM capacity beyond the variance explained by the binding factor, it would suggest that some process involved in this task, in particular, spatial inhibition has a unique contribution to PI resolution or WM beyond the contribution of the binding function. At the same time, If the binding factor significantly accounts for variance in PI resolution or WM capacity beyond the variance explained by the saccade-antisaccade task, it would suggest that binding has a unique contribution to PI resolution or WM beyond the contribution of the saccade-antisaccade task. Indeed, results of regression analyses (which will be discussed further below) supported the dissociation between the binding factor and the inhibitory function measured in the saccade-antisaccade task although these tasks both involve the processing of spatial information.

Mechanisms of PI Resolution

No dissociation between proactive and reactive control. First, results of the repeated measures ANOVAs failed to provide evidence for distinct proactive control and reactive control mechanisms. Although the PI effect was replicated in both the high and low proportion versions of all PI tasks, the study failed to find a smaller PI effect in the high interference proportion versions than the low proportion versions. Such findings are inconsistent with the prediction that

the high proportion version PI tasks, compared to the low proportion version PI tasks, would to a greater extent encourage the use of proactive control that can prevent PI and reduce the PI effect. Another piece of evidence is from the confirmatory factor analyses. The two-factor model consisting of two separate proactive and reactive factors did not fit the data significantly better than the one-factor model consisting of one common factor across both high and low proportion PI tasks.

Taken together, these results suggest that the manipulation of the proportion of interfering trials in the present study possibly did not selectively promote the use of proactive control or reactive control. Such a finding is inconsistent with Braver et al. (2007) in which the dissociation between proactive control and reactive control was observed by manipulating the proportion of interfering trials in the tasks. In their study, the PI effect tended to be smaller in the PI task with a high proportion of interfering trials than in the task with a low proportion of interfering trials, although this trend was not significant. More importantly, the better performance of high gF individuals in PI resolution compared to low gF individuals was not observed in the low proportion tasks (presumably measuring proactive control) but in the high proportion version (presumably measuring reactive control). However, in their study, the high proportion version of the PI tasks consisted of 80% interfering trials, while the proportion of interfering trials in the high proportion version of this study was 67%. It is possible that the proportion of interfering trials in this study was not high enough to promote proactive control. Therefore, two versions of PI tasks probably both mainly measured reactive control. Another possibility is that since the majority of participants in this study were students form Rice or other universities, it is possible that they are highly skilled at proactive control and are likely to engage this control to prevent upcoming PI regardless of the proportion of interfering trials. Indeed,

Braver et al. (2010) reported evidence for more engagement of proactive control after training emphasizing the use of proactive control. At the same time, reactive control was engaged to resolve the PI effect that was not completely prevented by proactive control. Therefore, the two versions of PI tasks may have both measured a combination of proactive control and reactive control.

Mechanisms of PI resolution. Since this study failed to find evidence for distinct proactive control and reactive control, regression analyses of PI resolution were conducted on a common factor of PI resolution.

If we assume that this common factor of PI resolution only reflects reactive control ability, the two accounts for reactive control – which are episodic inhibition and familiarity inhibition – can be evaluated. If the episodic inhibition account is correct, performance on inhibition tasks (i.e., tasks that only require an inhibitory function) should be correlated with performance on PI resolution. In addition, since PI arises due to interference between appropriate and inappropriate contextual bindings (according to the episodic inhibition account), the binding function should also be correlated with PI resolution. Even though the binding relations were not actively maintained in a process of proactive control to prevent PI (since the both versions of the PI tasks measured reactive control), these relations had to be encoded to meet the task goals. The better an item is associated with its appropriate context during encoding, the less PI would arise. In contrast, if the familiarity inhibition account is correct, performance on inhibition tasks should be correlated with performance on PI resolution. Performance on binding tasks, however, should not be correlated with performance on PI resolution since the PI effect arises due to conflict between response tendencies rather than due to the strength of binding relations.

The results of the regression analyses showed that, when controlling for performance on

tasks measuring storage and processing, binding and the performance on the anti-saccade task significantly predicted performance on PI resolution. Such findings support the episodic inhibition account since both binding and inhibition appear to play a role. Unfortunately when assuming both versions of the PI tasks mainly measured reactive control, no inferences could be made directly on the mechanisms of proactive control. However, if binding as a proactive control mechanism and episodic inhibition as a reactive control are indeed linked in PI resolution as proposed by the binding-episodic inhibition model, this model is supported by the findings of this study.

An issue worth discussing here is the nature of the inhibitory function. The results showed that the inhibitory process specifically involved in the saccade-antisaccade task plays a role in PI resolution. Why did performance in the other two inhibition tasks fail to predict the performance on PI resolution? First, these results are consistent with the findings from the confirmatory factor analyses on binding and inhibition. That is, the three tasks designed to measuring the inhibition function did not involve a common inhibitory process. For the letter flanker negative priming task, due to a lack of variance and reliability, it is difficult to evaluate whether the inhibitory process involved in this task contributes to proactive control. In contrast, the inhibitory process involved in the saccade-antisaccade task may specifically function upon spatial information, as discussed earlier. Importantly, inhibition on spatial information may also be involved in PI resolution, especially in the PI tasks used in the present task. Spatial information may serve as contextual cues to build the binding relations, especially when the items are presented at different locations as in the present study. For example, in the directed forgetting task, although color information is what is directly requested by the task goal, spatial information may also play a role. Instead of associating each item with its color (resulting in four

binding relations in a list of four words), participants could more efficiently group two items written in the same color according to their spatial arrangement and assign the color in which both items were written to each group (resulting in two binding relations; e.g., the top two words were written in blue while the bottom two words were written in red). Similarly, in the recent negatives tasks, spatial relationships between items could help group items in the same list so that the inhibitory function could be applied more effectively. By contrast, the inhibitory process involved in the Stroop task may function on verbal materials directly without any involvement of spatial information. Thus, individuals' performance on the Stroop task is less correlated with the PI tasks used in the present study. This idea can be tested using PI tasks that do not involve spatial information in further studies.

Although the episodic inhibition account is supported by the findings if one assumes that both versions of the PI tasks measured reactive control, it is also possible that both versions of the PI tasks measured a combination of proactive control and reactive control. If this were the case, it would be difficult to infer which function (i.e., binding or inhibition) is involved in proactive control and which function is involved in reactive control from the present results. Because the two dual mechanism models – the dual inhibition model and the binding-episodic inhibition model both predict the involvement of binding and inhibition, to test the two dual mechanism models it is crucial to examine which function – binding or inhibition is involved in proactive control vs. reactive control[5]. Since proactive control and reactive control could not be separated in this study, it would not be possible to distinguish the two dual mechanism models. Further studies that could successfully separate proactive control and reactive control are needed.

[5] Specifically, if inhibition were involved in proactive control, such a finding would support the dual inhibition model. Alternatively, if binding were involved in reactive control, such finding would support the binding-episodic inhibition account

Another interesting finding from these analyses is that, among the three measures of storage and processing, only category span significantly predicted PI resolution. The difference between these three measures is that each of them specifically measured storage and processing of a particular type of material (digit span: phonological representations; category span: semantic representations; matrix span: spatial representations). Therefore, the finding of a specific contribution of category span to PI resolution suggests that storage and processing of semantic representations is also important in PI resolution. This is consistent with the fact that two of the three PI tasks in the present study (i.e., the two tasks that loaded most heavily on the PI resolution factor) used words as stimuli. Different from most short memory tasks that mainly require rehearsal of phonological information, the PI tasks may require deeper processing of the binding relations. As a result, participants may process the words at the semantic level (deep processing, Craik & Lockhart, 1972) and use the semantic information to build the binding relations. For example, imagery, such as forming an image of a red apple may be used to associate the word "apple" with the red color.

PI resolution and working memory. The relation between PI resolution and WM capacity was replicated in the present study. If it is the case that both versions of the PI tasks measured reactive control, this finding indicates that reactive control ability is correlated with WM capacity. Such a finding is consistent with the inhibitory efficiency account (Hasher & Zacks, 1988) since inhibition is involved in both reactive control and WM. In contrast, this finding is inconsistent the resource-limited controlled attention theory (Engle et al., 1999). As discussed in the earlier sections, Braver et al. (2007) argued that proactive control is more resource-demanding than reactive control. If all types of resource-demanding control processes including proactive control and WM rely on a general controlled attention resource (i.e., the

resource-limited controlled attention theory), proactive control but not reactive control should be correlated with WM capacity. Therefore, given that PI resolution was correlated with WM, the two versions of the PI tasks in the present study might have measured a combined ability of proactive control and reactive control, which is indeed a possibility as discussed earlier. The correlation between PI resolution and WM found in the present study may be mainly driven by the relationship between proactive control and WM. Therefore, without separating proactive control and reactive control, it is difficult to distinguish the inhibitory efficiency theory and the resource-limited controlled attention theory from the present results of the correlation between PI resolution and WM capacity.

Interestingly, when including the binding factor, the saccade-antisaccade task, and storage and processing as predictors, there was no evidence for the contribution of performance on PI resolution to WM ability, while all the other predictors significantly predicted WM ability. These results indicate that the ability to resist PI is correlated with WM capacity because they both involve the processes involved in binding and inhibition. The role of inhibition in WM capacity has been reported by many previous studies. For example, individuals with high WM capacity exhibit better performance than individuals with low WM capacity on the Stroop and anti-saccade tasks where prepotent responses need to be inhibited (Kane et al., 2001; Kane & Engle, 2003). In addition, individuals with high WM capacity exhibit greater or more reliable negative priming effect than those with low WM capacity (Conway, Tuholski, Shisler, and Engle, 1999; Long & Part, 2002). A larger negative priming effect is assumed to reflect better inhibition ability; the better someone's ability to inhibit irrelevant information, the more difficulty he or she will have in identifying the previously inhibited item, and the larger the negative priming effect. However, in the present study, only performance in the saccade-

antisaccade task significantly predicted WM capacity, but not the Stroop or the letter flanker negative priming task. The low correlation between the letter flanker negative priming task and other tasks may be due to the restricted range of performance. For the Stroop task, the procedure used in the present study was different from that used in previous studies. That is, no congruent trials (e.g. "BLUE" written in the blue ink) were included in this study. Consistent with our results, Kane and Engle (2003) found that when there were no congruent trials in the Stroop task, there was no WM difference in error rates. They argued that demand on task goal maintenance is minimized in the Stroop task with no congruent trials because the task goal of ignoring the word itself would never be interrupted by the congruent trials in which participants would actually read the word. Therefore, the regular Stroop task (including congruent trials) at least partially measures the ability of maintaining task goals (also proposed in Friedman & Miyake, 2004) and the correlation between performance on the Stroop task and WM capacity is due to the commonly involved component of task goal maintenance. However, this account of goal maintenance could not explain the correlation between the saccade-antisaccade task and WM capacity. In the saccade-antisaccade task, each block consisted of only pro-saccade trials or only anti-saccade trials. Thus the task goal of looking away from the spatial cues for the anti-saccade trials would not be interrupted by the pro-saccade trials according to the idea of Kane and Engle (2003). Therefore, the correlation between this task and WM capacity cannot reflect the ability of maintaining task goals, but the ability of inhibiting preponent responses. It is still unclear, however, why the inhibitory process involved in the Stroop task to inhibit the tendency of naming words is not correlated with WM capacity. Further studies are needed to investigate this issue.

As for the implications of these results on WM theories, first these results are not

consistent with the inhibitory efficiency theory since not only inhibition but also binding was correlated with WM capacity. They seem to support the resource-limited controlled attention theory since both inhibition and binding play a role in WM. However, this study also demonstrated a dissociation between the binding function and the inhibitory function, which indicates they do not require a general attention resource. Taken together, the findings of the present study do not support the resource-limited controlled attention theory either. Instead, the present results suggest that the controlled processes include more functions than inhibition. Moreover, these functions such as inhibition and binding may be dissociable rather than based on one general limited attentional resource.

Nevertheless, it is important to note that only less than 30% of the variance in WM ability was explained by binding, inhibition, and storage and processing. Thus, these findings suggest there are other mechanisms involved in WM. For example, Salthouse (1996) proposed that a decrease of processing speed was the main source of decline of WM capacity in aging. Although I tried to control for the factor of storage and processing in the present study, the measures for this factor mainly tapped storage capacity but not processing speed.

In conclusion, the findings of the present study suggest that both inhibition and binding are involved in PI resolution. In addition, the correlation between PI resolution and WM capacity can be fully explained by the variation in binding and inhibition ability. Further studies that can separate proactive control and reactive control are needed to more definitively assess the dual mechanism models of PI resolution.

Chapter 3. Neural Basis of PI Resolution

As discussed in Chapter 1, neuroimaging evidence has provided support for the episodic inhibition account for reactive control. However, no neuroimaging study has examined the particular function, either binding or inhibition, for proactive control or their neural basis. Moreover, although the manipulation of the proportions of interfering trials in the individual differences study did not result in different use of proactive control and reactive control, if distinct proactive control and reactive control indeed exist they may be detected via the fMRI technique. Instead of using the behavioral index of the PI effect that reflects both proactive control and reactive control, the hemodynamic signals driven by the control process before the presentation of probes (i.e., proactive control) and the hemodynamic signals driven by the control process after the presentation of probes (i.e., reactive control) can be examined directly and separately using the fMRI technique. This fMRI study, therefore, examined the roles of binding and item inhibition in proactive control and the roles of familiarity inhibition and episodic inhibition in reactive control respectively.

An important methodological issue exists in examining proactive control using fMRI technique. That is, the conventional method of comparing interfering trials and non-interfering trials does not work in detecting regions involved in proactive control. Because participants do not know what probe will come up during the preparatory process of proactive control, they process both types of trials similarly (D'Esposito, Postle, Jonides, Smith, & Lease, 1999; Badre and Wagner, 2005). As a result, no difference for proactive control can be observed in the contrast between interfering trials and non-interfering trials. Therefore, although the left inferior frontal gyrus (LIFG: BA 45) has been repeatedly reported to be more active for recent negative trials than non-recent negative trials (i.e., revealing the brain activation correlated with the PI

effect; (Badre and Wagner, 2005; D'Esposito et al., 1999; Jonides et al., 1998; Jonides et al., 2000; Nee et al., 2007), these findings do not establish that the same brain region is also involved in proactive control.

To identify the regions responding to proactive control, Burgess & Braver (2010) designed a new contrast between two blocks of the recent negatives task with different proportions of recent negative trials. Since a high proportion of these trials (i.e., 80%) increases the likelihood that proactive control will be engaged, the region involved in proactive control should be more active during this block than during the block with a low proportion (i.e., 20%). The results of this study showed that, during retention intervals (when proactive control takes place), a region (BA9) of the right ventral lateral prefrontal cortex (VLPFC) not only exhibited greater activation in the high proportion block than the low proportion block (indicating its involvement in proactive control), but was also more activated for subjects with high general fluid intelligence (gF) than low gF subjects. Interestingly, after the presentation of the probe (when reactive control tasks place), a region (BA9) in the left VLPFC showed greater activation for recent negative trials than non-recent negative trials (indicating its involvement in reactive control), and also an effect of gF (high vs. low). Specifically, activation of this region was greater for low gF subjects than for high gF subject. This result indicates that high gF subjects resolve PI through proactive control that may be carried out by the right VLPFC, while low gF subjects resolve PI through reactive control that may be carried out by the left VLPFC. In addition to the right BA9, regions in bilateral dorsolateral prefrontal cortex (DLPFC), inferior frontal gyrus (IFG), supplementary motor area (pre-SMA), and right lateral parietal regions showed the same effect of the proportion of interfering trials during retention intervals regardless of the trial type and the gF level. Moreover, regions located within regions very similar to those

activated during proactive control, such as left DLPFC and lateral parietal lobe, right pre-SMA, as well as bilateral IFG, exhibited the effect of trial type (i.e., greater activation for recent negatives than non-recent negatives) after the presentation of the probe. Based on these findings, the authors concluded that proactive and reactive control involved some common brain regions, but also some distinct brain regions. However, this study did not try to examine what particular functions were involved in proactive control or reactive control.

In the present study, two approaches were used to examine proactive control and reactive control separately. First, the intervals between list onsets and probe onsets were jittered in addition to the intervals between trials. Thus, hemodynamic signals that were driven by the processes involved in proactive control could be separated from those driven by the processes involved in reactive control. Specifically, the hemodynamic signals arising immediately following the list onsets should reflect the processing involved in proactive control, whereas the signals following the probe onsets should reflect the processing involved in reactive control.

Then two types of contrasts were conducted to examine the functions involved in proactive control and reactive control, respectively. For proactive control, a PI task was compared with another task that put different demands on an inhibitory function involved in proactive control. The PI task that was carried out in this fMRI study is the directed forgetting task that was used in the individual differences study. This task is also often used as a measure of PI resolution (Oberauer, 2005). The other task is a color recognition task that involves somewhat similar processes to the local recognition task used in the individual differences study reported in Chapter 2.

In the directed forgetting task, words were presented in two different colors. Participants were asked to remember all words in the list. Then a color cue came up indicating which sub-list

(depending on the color) to remember (and consequently, which to forget). Although the directed forgetting task involves somewhat different processes than the recent negatives task, these two tasks would seem to involve very similar PI resolution mechanisms. For proactive control, on the one hand, subjects could suppress the memory of the to-be-forgotten items as soon as the color cue was provided (i.e., item inhibition). On the other hand, subjects could also strengthen the association between the items and their ink colors during the retention interval (i.e., binding). When the two potential proactive control mechanisms are not successfully applied, reactive control will come into play. In that case, PI will be caused by the high level of familiarity of the intrusion negatives (according to the familiarity inhibition account) or their link to irrelevant contextual information (i.e., the intrusion negatives are falsely linked to the cued color which produces a incorrect positive response according to the episodic inhibition account). An inhibitory function is needed to either inhibit the familiarity-based inappropriate response, or inhibit the inappropriate link to the irrelevant contextual information. In summary, as in the recent negatives task, both binding and item inhibition may be involved in the proactive control process in the directed forgetting task, while an episodic inhibitory process or a familiarity inhibitory process could be involved in reactive control. Moreover, since the directed forgetting task and the recent negatives task activate very similar brain areas (Nee et al., 2007), functions involved in proactive and reactive control in the directed forgetting task could be generalized to the recent negatives task.

In contrast, the color recognition task logically only involves binding as the proactive control mechanism, but not inhibition. A similar task – which is the local recognition task was used in the individual differences study as a binding task. These two tasks involve very similar processes. I used the color recognition task instead of the local recognition task to eliminate any

differences in brain activation caused by different task procedures (e.g., requiring memory of colors vs. memory of locations). Specifically, in the color recognition task, presentations of word lists were exactly the same as those in the directed forgetting task. Words were written in two different ink colors, either blue or red. No color cue, however, was presented following the presentation of the list. The task was to judge whether a probe written in one of the two colors (i.e., blue or red) appeared in the list and was written in the same color. Interference should occur when a probe was a member of the list but was written in a different color (termed an "intrusion negative"). Because no cue was provided to restrict the relevant item set, participants could not eliminate any items. If any of the items in the list were inhibited, subjects would make a negative response when the deleted word was presented as a probe (which would be wrong half the time), regardless of whether the probe was written in the matched or unmatched color. Therefore, item inhibition would not be beneficial in the color recognition task. In contrast, if the binding strength between items and their colors was strong, the association between the relevant item and its correct color would be less vulnerable to the intrusion of the word with the incorrect color. Thus, PI would be prevented. Otherwise, an episodic inhibitory function, as a reactive control mechanism, would have to step in to inhibit the link to the incorrect contextual information. Therefore, only binding could serve as the proactive control function and only episodic inhibition could serve as the reactive control function in this task.

In sum, one key difference between the two tasks employed in the present study is that for proactive control, the directed forgetting task may involve either binding or item inhibition, whereas the color recognition task should logically involve the binding function but not item inhibition. Therefore, in terms of neural signals following list onsets (i.e., those reflecting proactive control), if the same brain regions are engaged in both tasks, it would indicate that the

same proactive control function (i.e., binding) is involved in resolving PI in both tasks as a proactive control mechanism. By contrast, if different brain regions are engaged in the two tasks, it would suggest that different proactive control mechanisms are involved. Item inhibition is, after all, more important in PI resolution in the directed forgetting task, while only binding should be involved in the color recognition task.

For regions that may be involved in inhibition, previous studies have identified multiple candidate regions in the prefrontal cortex. For example, the bilateral inferior frontal cortex, DLPFC, and the anterior cingulate cortex (ACC) were found to be more active during tasks where inhibition was required to suppress a prepotent response tendency, such as for the GO/NO-GO task and the Stroop task (Aron, Robbins, & Poldrack, 2004; Nee et al., 2007). In addition, Kuhl, Dudukovic, Kahn, and Wagner (2007) found evidence that the ACC and bilateral DLPFC were involved in suppressing more abstract memory representations.

As for the binding function, one relevant area of research includes studies examining episodic memory encoding. Since binding as a proactive control process takes place during encoding and maintaining the item-context association that is also critical for episodic memory, regions involved in episodic memory encoding may also be responsible for binding. Areas that have been repeatedly reported to be involved in episodic memory encoding include multiple prefrontal regions (such as the VLPFC, DLPFC, and anterior prefrontal cortex; Blumenfeld & Ranganath, 2007; Cansino, Maquet, Dolan, & Rugg, 2002; Mitchell, Johnson, Raye, & Greene, 2004; Ranganath, Johnson, & D'Esposito, 2003; Slotnick, Moo, Segal, & Hart Jr., 2003; Spaniol et al., 2009), the posterior parietal cortex, and the medial temporal cortex (Spaniol et al., 2009). Regions in the prefrontal cortex, however, do not seem to be the storage site of memory representations or directly involved in integrating relevant features. Instead, the prefrontal cortex

is specifically responsible for resolving interference (e.g., inhibiting the interfering contextual information) in episodic memory. King, Hartley, Spiers, Maguire, and Burgess (2005) provided evidence for this argument showing that prefrontal activation was greatly reduced when one item corresponded to only one context vs. when the same item was presented in a number of different contexts. Since the proposed study used a large stimulus pool ensuring that each word only appeared once in the word list, no single word was presented in different colors. Thus, no interference would occur during encoding. Therefore, prefrontal regions are not expected to be involved in the binding process.

In contrast, evidence from previous studies suggests that the posterior parietal cortex may be involved in the use of binding as a mechanism of proactive control. First, activation in this area has been reported during visual search tasks that require feature binding (Nobre, Coull, Walsh, & Frith; 2003; Shafritz, Gore, & Marois, 2002). Second, this region has been found to be frequently activated during encoding and retrieval of episodic memories in tasks that emphasize the binding of content and contextual information (Cabeza, Ciaramelli, Olson, & Moscovitch, 2008; Uncapher & Wagner, 2009; Wagner, Shannon, Kahn, & Buckner, 2005). One hypothesis regarding the role of this area in episodic memory is that these parietal regions might contribute to shifting attention between internal representations of multiple relevant features (Wagner et al., 2005), since attention to all relevant features is required to build association among them.

In summary, multiple regions in the prefrontal cortex should be involved in item inhibition whereas only the posterior parietal cortex is expected to be involved in binding during proactive control. If it is true that the same function is involved in both tasks (i.e., binding), both tasks should activate the posterior parietal region but no difference should be found in activation between the two PI tasks in this region, since binding is carried out in this region. If binding

alone is involved in proactive control in both tasks (i.e., the directed forgetting task does not also involve item inhibition), then there should be no difference in activation in the prefrontal cortex either. Alternatively, if item inhibition is involved in PI resolution in the directed forgetting task, the prefrontal cortex should be more activated for the directed forgetting task compared to the color recognition task. At the same time, since binding plays a greater role in the color recognition task than the directed forgetting task the posterior parietal cortex should show greater activation for the color recognition task than the directed forgetting task. .

One issue that comes up in the comparison between the directed forgetting and the color task is the effect of set size during memory retention. If item inhibition is indeed involved in the directed forgetting task, after participants successfully delete the irrelevant items, they only need to hold on to half of the list in memory. In contrast, in the color recognition task, the whole list needs to be maintained. Consequently, greater activation observed in the color recognition task could simply be caused by greater task difficulty due to a larger set size. To address this issue, half of the trials in the color recognition task consisted of two word lists, while the other half consisted of four word lists. In contrast, all trials in the directed forgetting task consisted of four word lists. This design allowed a conjunction analysis that could rule out regions involved in a set size effect.

Finally, a simple recognition task that was modified from the study of Oberauer (2005) was also included in the study as a baseline task. The procedure for this task is very similar to the two other recognition tasks. One difference is the task goal. In this task, subjects were asked to judge whether a probe was presented in the list regardless of its ink color. Thus, what were intrusion negatives in the color recognition task would be positive probes in the simple recognition task, because subjects should make a positive response as long as the probe is a

member of the list even though its ink color is different from that in the list. Therefore, this task minimized the role of interference and thus put the lowest demand on control processes, including both proactive and reactive control. This task was included so that regions involved in binding could be identified by comparing the color recognition task with the baseline task. This contrast is especially useful if binding is indeed involved in both the directed forgetting task and the color recognition task and no difference in binding regions could be observed between these two tasks.

As for reactive control, the conventional contrast between the intrusion negative trials and the control negative trials was examined in signal changes following the onset of the probes. Both accounts of reactive control predict an inhibitory function. The episodic inhibition account, however, also predicts involvement of binding, since the episodic inhibitory function acts upon binding relations. By contrast, familiarity inhibition does not involve binding, but only an inhibitory function. If the regions exhibiting greater activation for intrusion negative trials than control negative trials are associated solely with inhibitory functions but are not involved in binding, the familiarity inhibition hypothesis would be supported. In contrast, if some of these regions are involved in inhibition and some are engaged in binding, these findings would indicate that the inhibitory function acts upon the inappropriate binding relations between items and contextual information. This idea would be in line with the episodic inhibition account. By only examining the contrast between intrusion trials and control trials, however, it is difficult to provide independent support for their function (i.e., inhibition or binding) beyond what is suggested by prior literature since no manipulation was done on inhibition or binding in this contrast. However, the findings from the proactive control analyses could aid in this analysis since the demands for inhibition and binding were manipulated with respect to proactive control.

Therefore, to distinguish the familiarity inhibition and episodic inhibition account for reactive control, regions identified in this reactive control contrast were overlapped with the regions of inhibition and regions of binding identified in the proactive control contrasts. Again, if the regions of reactive control only overlap with regions of inhibition (presumably the prefrontal cortex), the result would support the familiarity inhibition account. If the regions of reactive control overlap with regions of binding (presumably the posterior parietal cortex) in addition to regions of inhibition, such a finding would support the episodic inhibition account.

After the mechanisms involved in proactive control and reactive control are identified, the two dual mechanism control model could be evaluated. If the dual inhibition model is true, item inhibition should be involved in proactive control in the directed forgetting task, while familiarity inhibition should be involved in reactive control. Alternatively, if the binding-episodic inhibition model is true, binding should be involved in proactive control in the directed forgetting task, while episodic inhibition should be involved in reactive control.

Last, a rehearsal localizer task was also conducted. Since a rehearsal strategy is often applied in verbal work memory tasks, it is possible that regions responsible for rehearsal would be more activated in more difficult conditions/tasks than in less difficult conditions/tasks. So regions involved in rehearsal may also be activated in the contrasts of interest, and thus contaminate the results. More importantly, regions in left inferior frontal cortex (BA 44; Ravizza, Delgado, Chein, Becker, Fiez, 2004) where inhibition has been localized have often been reported in rehearsal tasks. If the regions identified in the left inferior frontal cortex are indeed engaged in inhibition but not rehearsal, they should be separate from the regions identified in the rehearsal localizer task.

Method

Participants

Sixteen English native speakers with normal color vision were scanned in this study. Participants were recruited from undergraduate and graduate student population at Rice University. Subjects were screened using a detailed questionnaire to ensure that they had no history of neurological or psychiatric problems. Subjects were compensated with $30 for a two-hour session, including .5 hr for practice outside the scanner and 1.5 hrs for scanning. Data from three subjects were excluded due to uncorrectable head movement. The age range of participants whose data were included is 18-30. Among these thirteen participants, six were males and seven females. In addition, one female subject withdrew from the experiment before she completed the rehearsal localizer task.

All subjects were native English speakers. Additionally, all subjects were right-handed and had normal or corrected-to-normal vision. Informed consent was obtained from each subject in accordance with the guidelines and approval of the Rice University Institutional Review Board.

Materials

Three hundred and six English concrete nouns with one or two syllables and four to six letters in length were used as stimuli (K-F frequency 3-393 occurrences per million (Kucera and Francis, 1967; http://www.psy.uwa.edu.au/mrcdatabase/uwa_mrc.htm)) in the three recognition tasks. Each word only appeared once in each task except for words that served as probes in the positive and intrusion negative trials. All 306 words appeared in the directed forgetting tasks, while a aubset of these words appeared in the color recognition and simple recognition tasks since half the trials in these tasks only consisted of two-word lists. In the trials consisting of two-word lists, two symbol strings of "ΩŒ§$&" were presented simultaneously with the two real words to match the visual complexity of the four-word lists. In addition, words were regrouped

into four-word lists or two-word lists across tasks. Therefore, no word list that consisted of the same words was presented in two tasks. The average word length, number of syllables, frequency, and imageability of word lists and those indices of probes were matched across tasks, trial types, and between set sizes within the color recognition and simple recognition tasks.

In addition, each task consisted of 18 positive trials, 18 control negative trials, and 36 intrusion negative trials. In the color recognition and simple recognition tasks, half the trials in each condition consisted of four-word lists, while the other half consisted of two-word lists. The proportion of interfering trials was set to a medium level (i.e., 50%) so that participants were likely to apply both proactive and reactive control.

In the rehearsal task, ten letter strings consisting of three letters randomly chosen from letters A-G without replacement were used as stimuli.

Procedure

Three recognition tasks and a rehearsal task were conducted. The three recognition tasks followed very similar procedures. Each trial started with a word list where four words/symbol strings were presented in a 2 by 2 matrix which stayed on the screen for 2.5 seconds. The top two words (or two words in the left column) were written in a different color from the bottom two words (or two words in the right column), either in red or blue. However, which row or column was in blue or red was randomized, so that the color of any word could not be predicted by its location. Following a 1000 ms fixation after the offset of the list, a colored frame (i.e., the cue) was presented at the center of the screen. After the cue that was presented for varied durations (400/2400/4400 ms), a 100 ms fixation appeared at the center of the frame with the frame remaining on the screen. Then with the frame staying on the screen, a colored probe word was presented at the center of the screen. Participants were asked to respond to the probe word as fast

and as accurately as possible according to the task instructions. Both the frame and the probe remained on the screen for 1000 ms, followed by the inter-trial intervals that were jittered as 1000 ms, 3000 ms, and 5000 ms. The average jittered durations were matched among conditions.

In the directed forgetting task, the colored frames were presented in either blue or red ink. The probe was always presented in the same color as the frame. The participants were asked to determine whether the probe appeared in the current list and at the same time was written in the cued color. For positive trials, the probe was a word that written in the cued color in the current list. For control negative trials, the probe was a word that was not presented in the current list. For intrusion negative trials, the probe was a word in the list but written in the un-cued color. The procedure for each trial is illustrated in Figure 3.1.

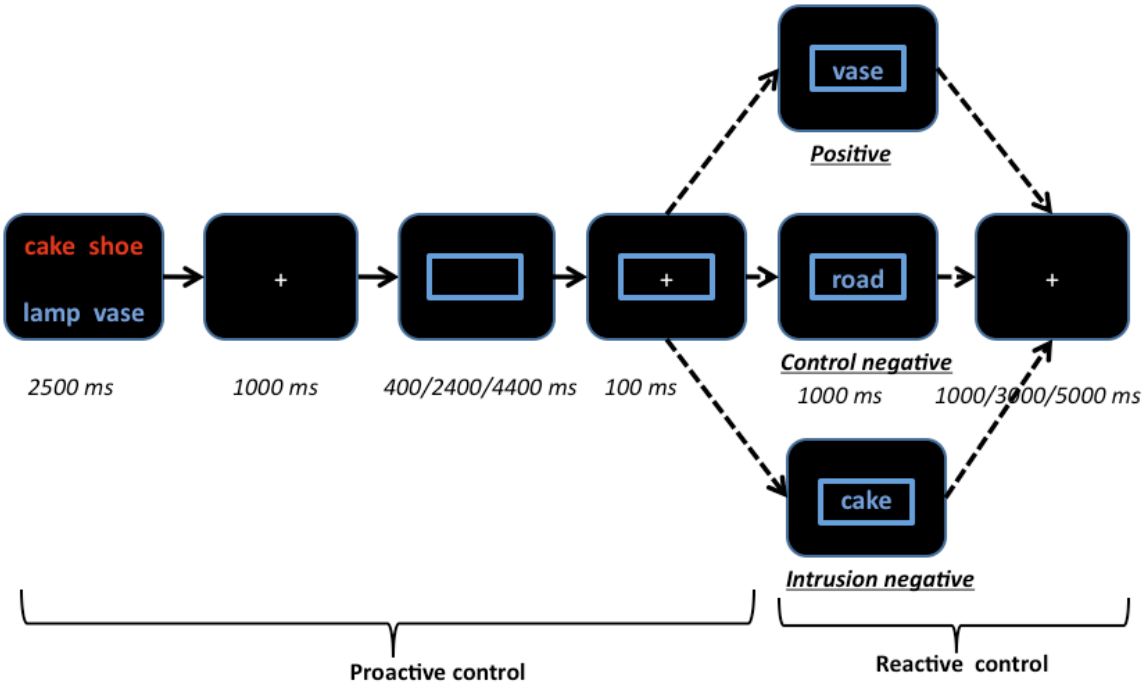

Figure 3.1. Sequence of trial events in the directed forgetting task.

In the color recognition task, all color frames were presented in yellow, and the subjects were told that the color of the frame would not provide any information about the task or indicate

the color of the probe. The probes were presented in either blue or red ink. The task was to determine whether the probe appeared in the list and in the same color. For the positive trials, the probe was a word in the current list in the same color. For the control negative trials, the probe was a new word that did not appear in the list. For the intrusion negative trials, the probe was a member of the current list, but in a different color. The procedure for each trial is illustrated in Figure 3.2.

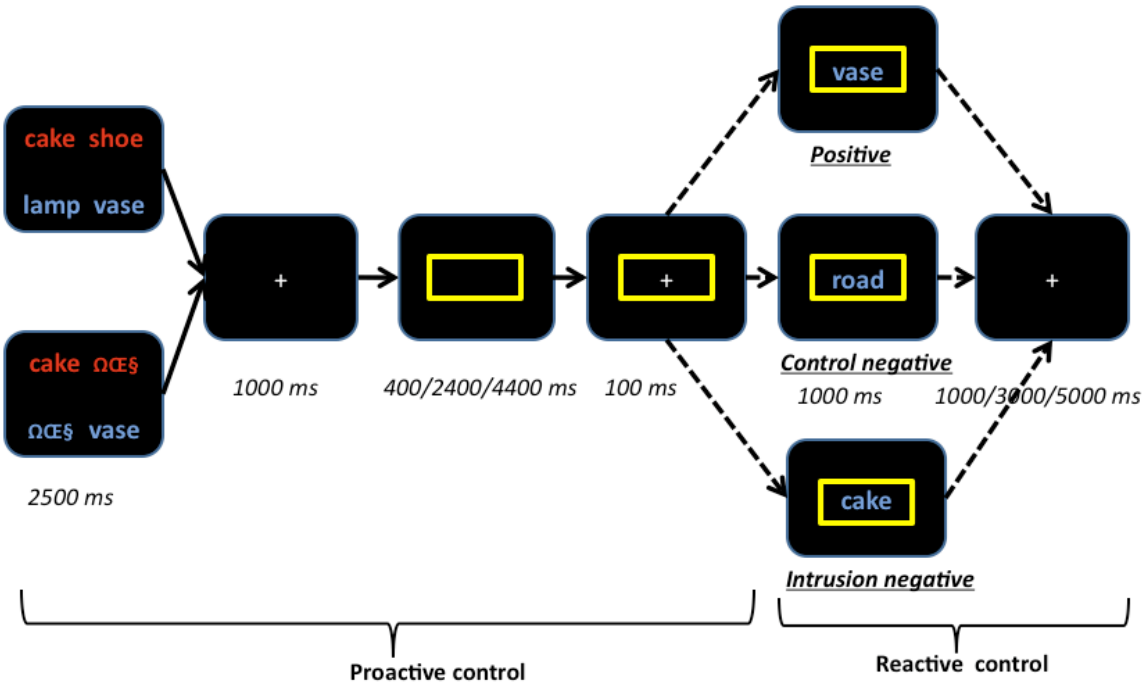

Figure 3.2. Sequence of trial events in the color recognition task.

In the simple recogniton task, all probes and cues were presented in yellow. Subjects were asked to simply make a judgment on whether the probe was in the current list. The intrusion negative probes in the color recognition task were all positive probes in the current task. The control negatives were still negative probes. And the positive probes were still positive probes. So there were 54 positive probes, and 18 negative probes. The procedure for each trial is illustrated in Figure 3.3.

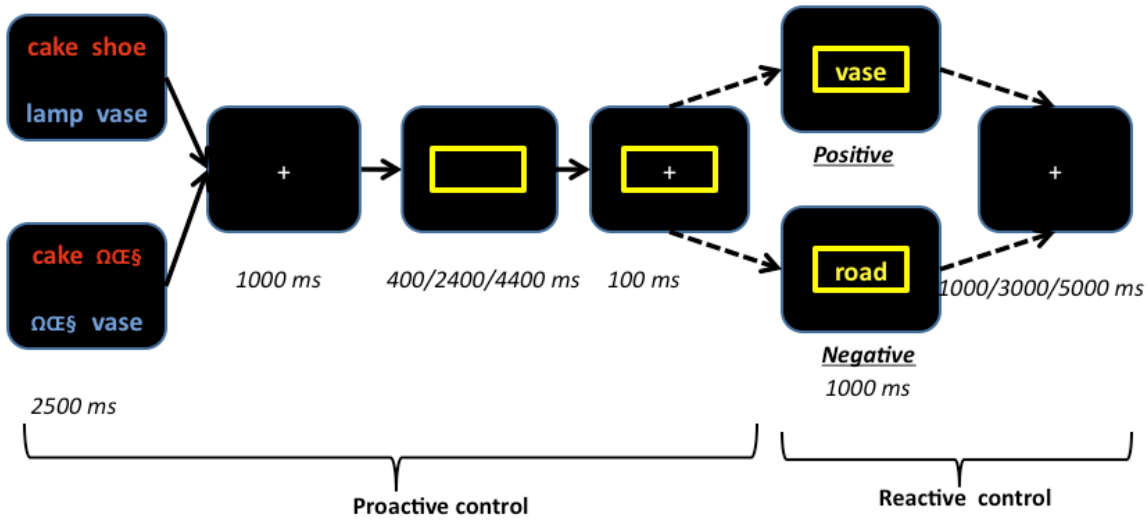

Figure 3.3. Sequence of trial events in the simple recognition task.

Importantly, for all tasks, none of the negative probes appeared in the preceding list. Therefore, interference from the memory of the preceding list was minimized.

The three recognition tasks were presented in six runs. Each run contained 12 successive trials of each task, including three positive trials, six intrusion negative trials and three control negative trials (for the directed forgetting task and the color recognition task), or nine positive trials and three negative trials (for the color recogniton task). In the first three runs, all trials consisted of four-word lists. In the last three runs, trials in the directed forgetting task still consisted of four-word lists, whereas those in the color recognition and simple recognition tasks trials consisted of two-word lists. Before the first trial of each task, a task instruction was presented for 4000 ms as "color recognition" (for the color recognition task), "simple recognition" (for the simple recognition task) and "cue-based recognition" (for the directed forgetting task) to indicate the following task. The order of tasks within each run was counterbalanced.

After the six runs of the recognition tasks, the rehearsal task was conducted in a blocked design. In this task, each letter string was presented at the center of the screen for 4000 ms, immediately followed by the next letter string. Two types of blocks were conducted with five letter strings presented in each. At the beginning of a rehearsal block, participants received an instruction "$$ rehearsal", indicating that they should rehearse each following letter string at their own pace until a different instruction appears. In contrast, at the beginning of a no-rehearsal block, an instruction of "No rehearsal" was presented asking participants to passively watch the presentation of each letter string without rehearsing them until a different instruction appears. Each block repeated for four times in the sequence of "ABBAABBA", with a 22 s rest block (fixation only) between every two task blocks. Within subjects, each letter string that was presented in the rehearsal block never appeared in the no-rehearsal block or vice versa. Between subjects, which list of five letter strings was presented in the rehearsal block vs. no-rehearsal block was counterbalanced. Before each task block, a 22 s fixation block was presented during which participants were asked to gaze at the fixation point.

Participants completed practice for each task outside the scanner prior to the scan. For the three recognition tasks, they first completed 12 trials of each individual task, and then practiced a block with the three tasks presented successively as in the scanning runs. During the practice, participants were familiarized with the task instructions and asked to describe the meaning of each task's instructions before and after the practice trials. No participant showed any difficulty in understanding or remembering the task instructions. For the rehearsal task, participants were shown a demonstration of the rehearsal, no-rehearsal, and fixation blocks. During the demonstration of each block, they were told what task they were supposed to do. In addition, they were informed that they were going to be tested after the scan on the letter strings that they

were asked to rehearse, so that they would have to engage rehearsal when they were instructed to do so.

None of the stimuli that appeared in the practice were used in the actual tasks.

Image Acquisition and Analysis

Scanning was conducted at the Baylor Neuroimaging Center at Baylor College of Medicine on a Siemens 3T Allegra scanner (Erlangen, Germany). At the beginning of each run, there was an 8 s fixation to allow for stability in magnetization. At the end of each run, there was a 14 s fixation to compensate for the delay of the hemodynamic response. Anatomical images were acquired first, using a transverse MP-RAGE T1-weighted sequence (Siemens) with a voxel size of .5 x .5 x 1 mm (TR = 1200 ms; TE = 2.93 ms; flip angle = 12°). Functional images were acquired using an echo-planar sequence (TR = 2000 ms; TE = 40 ms; flip angle = 90°; voxel size = 3.5 x 3.5 in-plane resolution). During each functional run of the recognition tasks, 198 sets of 26 contiguous 4-mm thick axial images were acquired, while during the functional run of the rehearsal task, 188 sets of images were acquired. Visual stimuli were projected onto a screen using an LCD projector and viewed through a mirror attached to the head coil.

Imaging data were analyzed using the AFNI analysis package (Cox, 1996). The first 4 slices were excluded from the analysis. Preprocessing for each participant followed a script generated by the AFNI program afni_ proc.py. Voxel time series were aligned to the same temporal origin using the AFNI program 3dTshift and the quintic Lagrange polynomial interpolation option. For each EPI run, each 3d volume from the input dataset was registered to the volume acquired in closest temporal proximity to the T1-weighted anatomical scan (the first volume of the first EPI scan) using the AFNI program 3dvolreg with the cubic polynomial interpolation option. A 6-mm full-width half maximum (FWHM) Gaussian blur was then applied using AFNI's 3dmerge

program. The data were then scaled in order to calculate the percentage signal change. Preprocessed data were analyzed based on the General Linear Model (GLM; Friston et al., 1994; Josephs, Turner, & Friston, 1997; Miezin, Maccotta, Ollinger, Petersen, & Buckner, 2000; Worsley & Friston, 1995; Zarahn, Aguirre, & D'Esposito, 1997), using AFNI's 3dDeconvolve program.

For the rehearsal localizer task, the deconvolution analysis estimated the BLOCK impulse response function (IRF) for each unique condition (i.e., rehearsal vs. non-rehearsal condition) with 22 s duration for each block. The deconvolution analysis produced an IRF for each condition at each voxel. In addition, six motion factors and baseline drifts were also estimated and included in the model. All effects were modeled simultaneously in the GLM for each subject. The Beta values for the BOLD signals generated by the GLM were submitted to an analysis of variance (ANOVA) using AFNI's 3dANOVA program.

For the recognition tasks, the deconvolution analysis estimated the TENT-zero impulse response function (IRF) for each unique condition (this function corrected signals at the first and last time point to zero), with no assumptions regarding the shape of the function, at the 8 time points (i.e., image acquisitions) immediately following the onset of the lists, and at the 7 time points immediately following the onset of the probes. Six conditions were modeled for hemodynamic signals immediately following the list onsets. There were two run positions (the first three runs vs. in the last three runs) in each of the three tasks (directed forgetting vs. color recognition task vs. simple recognition). Eight conditions were modeled for signals following the probe onsets: 2 Tasks × 3 Conditions (Task: directed forgetting vs. the color recognition ; Conditions: positive vs. the control negative vs. the intrusion negative) in addition to 2 Conditions (positive vs. negative) in the simple recognition task. Incorrect trials were modeled

separately. The deconvolution analysis produced an IRF for each condition at each voxel. In addition, six motion factors and baseline drifts were also estimated and included in the model. All effects were modeled simultaneously in the GLM for each subject. The intensity values for the BOLD signal peak (4-12s post list onsets, 4-8s post probe onsets) were averaged for each condition at each voxel, and these values were submitted to an analysis of variance (ANOVA) using AFNI's 3dANOVA program. Incorrect trials were modeled in the deconvolution analysis, but not included in the ANOVA.

Results

Imaging Data for the Rehearsal Localizer Task

A whole-brain contrast between the rehearsal condition and the non-rehearsal condition was conducted on the beta values generated by the GLM. Multiple comparisons were corrected by the activation threshold of 0.005 and cluster size of 24 voxels, resulting in a corrected *p*-value of 0.01. No regions showed significantly greater activation for the rehearsal condition compared to the non-rehearsal condition. Nine regions were more activated in the non-rehearsal condition relative to the rehearsal condition.

These unexpected results may be due to poor control of the non-rehearsal task and the rest blocks. Participants perhaps engaged more rehearsal of target letter strings during the non-rehearsal blocks (perhaps also in the rest blocks) in order to better maintain the targets and prevent forgetting. Only when comparing the rehearsal condition with the rest blocks using a lower threshold $p_{(\text{uncorrected})} < 0.05$, were bilateral inferior frontal regions identified (centered at -53, 8, 6: BA44; -41, 8, 30: BA9; 53, 14, 3: BA45). Other regions showing greater activation during rehearsal compared to baseline are listed in Table 3.1.

Table 3.1

Regions identified in the rehearsal condition (compared to fixations).

	Hemisphere	Coordinates (x, y, z)	BA	Name	# of Voxels
Rehearsal > Fixation	Left	-2, 11, 42	32	Cingulate Gyrus	171
		-32, -80, -10	19	Fusiform Gyrus	90
		-38, -44, -22		Culmen	89
		-41, 8, 30	9	Inferior Frontal Gyrus	67
		-11, 29, -25		Culmen	31
		-50, 11, 3	44	Inferior Frontal Gyrus	29
	Right	32, -80, -13	19	Fusiform Gyrus	142
		50, 17, 3	45	Inferior Frontal Gyrus	26

Note. Coordinates are given in standardized space (Talairach & Tournoux, 1988); BA refers to the approximate Brodmann's area.

Behavioral Performance on the Three Recognition Tasks

Accuracy and reaction times were recorded (see Figure 3.4a for accuracy; see Figure 3.4b for reaction times).

Overall performance across the three tasks. Overall performance was analyzed to determine the relative difficulty of the tasks across the different runs. Values of *d'* were calculated for each subject is the first three runs and the last three runs respectively collapsing across different types of negative and positive probe trials. Two-way repeated measures ANOVAs of Task (directed forgetting vs. color recognition vs. simple recognition) × Run Position (the first three vs. the last three) were conducted on the values of *d'*. The main effect of Task was significant, $F(2, 24) = 18.98$, $p < .001$, $\eta^2_{partial} = .03$, . Post-hoc tests of contrasts were analyzed via paired-sample *t*-tests (Corrected by Bonferroni adjustment; $p < .016$ to be significant). Participants were more sensitive in recognizing old items in the simple recognition

task than in the directed forgetting task ($F(1, 12) = 25.48$, $p < .001$, $\eta^2_{partial} = .68$) and the color recognition task ($F(1, 12) = 45.93$, $p < .001$, $\eta^2_{partial} = .79$). Participants' sensitivity did not differ significantly between the directed forgetting task and the color recognition task, $F(1, 12) = .15$, $p = .71$, $\eta^2_{partial} = .01$. The main effect of Run Position was also significant, $F(1, 12) = 10.73$, $p = .01$, $\eta^2_{partial} = .47$. Participants were more sensitive in the last three runs than the first three runs, likely due to a practice effect. The interaction effect between Task and Run Position was not significant, $F(2, 24) = 3.27$, $p = .06$, $\eta^2_{partial} = .21$.

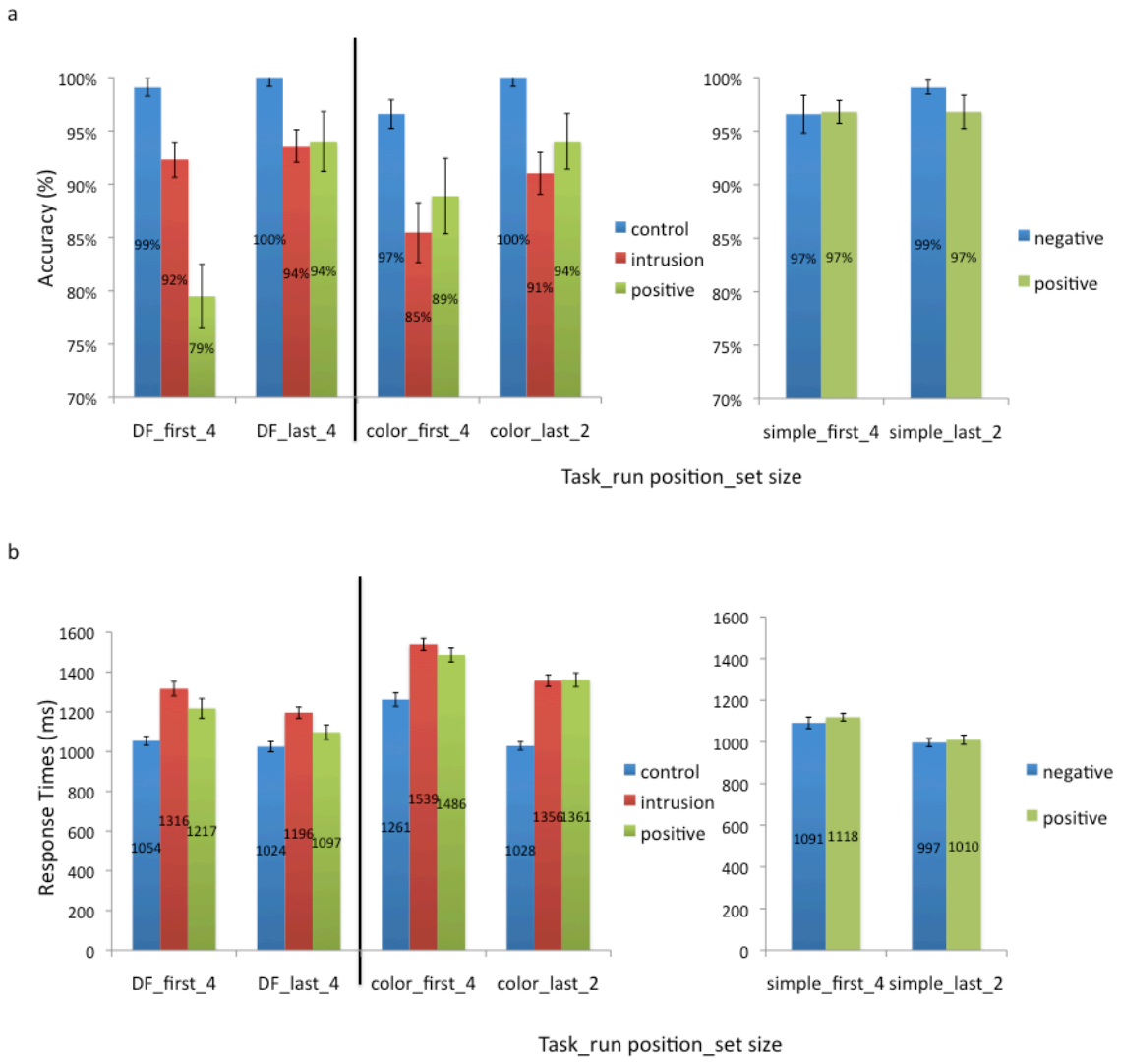

Figure 3.4. a) Accuracies. b) response times. "DF": the directed forgetting task; "color": the color recognition task; "simple": the simple recognition task. "First": the first three runs; "last": the last three runs. "4": four word list; "2": two word list. Error bars represented standard errors corrected for between-subject variability.

In addition, the mean response times were analyzed via a three-way repeated measures ANOVA of Task (directed forgetting vs. color recognition vs. simple recognition) × Probe Type (negatives vs. positives) × Run Position (the first three vs. the last three). In the directed forgetting and the color recognition tasks, the negative trials included both the control negative

trials and the intrusion negative trials. The main effect of Task was significant, $F(2, 24) = 57.19$, $p < .001$, $\eta^2_{partial} = .88$. Post-hoc tests of contrasts showed that participants responded faster in the simple recognition task than the directed forgetting task, $F(1, 12) = 13.42$, $p = .003$, $\eta^2_{partial} = .53$, and the color recognition task, $F(1, 12) = 135.94$, $p < .001$, $\eta^2_{partial} = .92$. They also responded faster in the directed forgetting task than in the color recognition task, $F(1, 12) = 37.41$, $p < .001$, $\eta^2_{partial} = .76$). All tests of contrasts were corrected by Bonferroni adjustment ($p < .016$ to be significant). The main effect of Run Position was also significant, $F(1, 12) = 33.61$, $p < .001$, $\eta^2_{partial} = .74$. Participants responded faster in the last three runs than the first three runs, likely due to a practice effect. There was also a significant main effect of Probe Type, $F(1, 12) = 10.33$, $p = .01$, $\eta^2_{partial} = .46$. Participants responded faster for negative trials compared to positive trials. In addition, the interaction between Task and Probe Type was significant, $F(2, 24) = 5.35$, $p = .01$, $\eta^2_{partial} = .31$. Therefore, two-way repeated measures ANOVAs of Probe Type (negatives vs. positives) × Run Position (the first three vs. the last three) were conducted for each task. The main effect of Probe Type was only significant in the color recognition task. That is, response times were faster for the negative trials than for the positive trials, $F(1, 12) = 13.45$, $p = .003$, $\eta^2_{partial} = .53$. In contrast, there was no significant difference between the negative and positive trials in either the directed forgetting task, $F(1, 12) = .11$, $p = .75$, $\eta^2_{partial} = .01$, or in the simple recognition task, $F(1, 12) = 1.16$, $p = .30$, $\eta^2_{partial} = .09$. None of the other interaction effects in the three-way ANOVA analysis was significant (Run Position × Task: $F(2, 24) = 2.08$, $p = .15$, $\eta^2_{partial} = .15$; Run Position Trial Type: $F(1, 12) = .08$, $p = .78$; three-way interaction: $F(2, 24) = 3.15$, $p = .06$, $\eta^2_{partial} = .21$).

PI effects in the directed forgetting task and the color recognition task. Accuracy and response times were analyzed via three-way repeated measures ANOVAs of Task (directed

forgetting vs. color recognition) × Probe Type (control negative vs. intrusion negative) × Run Position (the first three vs. the last three).

For accuracy, there were a significant main effect of Task (i.e., greater accuracy in the directed forgetting task than in the color recognition task), $F(1,12) = 7.72$, $p = .02$, $\eta^2_{partial} = .39$; a main effect of Run Position (i.e., greater accuracy in the last three runs than in the first three runs), $F(1, 12) = 6.64$, $p = .02$, $\eta^2_{partial} = .36$, and a main effect of Probe Type, $F(1, 12) = 30.19$, $p < .001$, $\eta^2_{partial} = .72$. Participants made more errors for the intrusion negative trials than the control negative trials. None of the interaction effects was significant.

For response times, again, there were significant main effects of Task, $F(1,12) = 25.39$, $p < .001$, $\eta^2_{partial} = .68$, Run Position, $F(1, 12) = 64.70$, $p < .001$, $\eta^2_{partial} = .01$, and Probe Type, $F(1, 12) = 101.10$, $p < .001$. The directions of these effects were consistent with the findings on accuracy. In addition, the interaction between Task and Probe Type was also significant, $F(1, 12) = 7.18$, $p = .02$, $\eta^2_{partial} = .37$. Tests of the simple effect of Probe Type showed that participants responded faster for the control negative trials than for the intrusion negative trials in both tasks (directed forgetting: $t(12) = 6.56$, $p < .001$, $d = 1.82$; color recognition: $t(12) = 10.76$, $p < .001$, $d = 2.99$). The significant interaction indicated, however, that the effect was larger in the color recognition task. This result might imply that different control mechanisms were involved in the two tasks, and the control mechanism of item inhibition involved in the directed forgetting task was more efficient in resolving PI. In addition, the interaction between Task and Run Position was significant, $F(1, 12) = 10.13$, $p = .01$, $\eta^2_{partial} = .46$. The three-way interaction was also significant, $F(1, 12) = 4.79$, $p = .049$, $\eta^2_{partial} = .29$. These effects were not further examined since they are not relevant to the effect of interests.

Analysis of Imaging Data Following List Onsets (Proactive Control) in the Three

Recognition Tasks

Following the onset of lists, two whole-brain contrasts were conducted to identify regions of inhibition and regions of binding respectively on the mean of hemodynamic responses from the second to the sixth time points (i.e., 4-12s). Multiple comparisons were corrected by the activation threshold of 0.01 and cluster size of 34 voxels, resulting in a corrected *p*-value of 0.01. Then, the hemodynamic response was extracted from each region with fixations as baselines. The interaction between the effect of task (the directed forgetting task vs. the color recognition task) and quadratic contrast effect of time (across the 8 estimated time points following the onset of lists) was assessed in each region. Only regions exhibiting a significant interaction effect ($p < .05$) and with the maximum BOLD signal exceeding |0.15| will be reported. These criteria were applied to ensure that the identified regions exhibit reasonable hemodynamic signal changes, and that the effect of interests occurred due to signal changes driven by the stimulus events but not due to random signal fluctuations.

Contrast of inhibition. To identify regions of inhibition, the directed forgetting task with four-word lists in the last three runs was compared with the color recognition task with two-word lists in the last three runs. The analyses on the behavioral performance showed that the errors (examined by *d'*) did not differ between these two conditions, although the response times were faster for the directed forgetting task than for the color recognition task. Since participants only needed to maintain half of the lists (i.e., two words) in the directed forgetting task if they indeed engaged the inhibitory control function, whereas they needed to remember the whole list in the color recognition task (i.e., again two words), the set sizes during retention were matched between the two tasks. Regions involved in inhibition should show greater activation during the directed forgetting task than the color recognition task, since inhibition can only be involved in

the directed forgetting task but not in the color recognition task. Eight regions were identified in this contrast. All regions showed greater activations in the directed forgetting task than the color recognition task. Two of these regions were in the left inferior frontal gyrus (centered at -38, 11, 27: BA44 & -35, 26, 6: BA 45). In addition, a region in the left inferior parietal lobe also exhibited an effect of inhibition (centered at -47, -50, 57: BA40). Other regions identified in this contrast included the precentral gyrus, the postcentral gyrus, the lingual gyrus, and the cingulate gyrus. Details on these regions are listed in Table 3.2.

Table 3.2

Regions identified in the contrast between the four-word-list directed forgetting task and two-word-list color recognition task in the last three runs.

	Hemisphere	Coordinates (x, y, z)	BA	Name	# of Voxels
	Left	-53, -11, 51	3	Postcentral Gyrus	101
(Activation)		-47, -50, 57	40	Inferior Parietal Lobule	72
Four-word-list directed		-38, -11, 54	6	Precentral Gyrus	62
forgetting task		**-37, 11, 27**	**44**	**Inferior Frontal Gyrus**	**49**
>		**-35, 26, 6**	**45**	**Inferior Frontal Gyrus**	**43**
Two-word-list color	Right	5, -74, 3	18	Lingual Gyrus	264
recognition task		2, 11, 39	32	Cingulate Gyrus	200
		56,2,45	6	Precentral Gyrus	56

Note. Coordinates are given in standardized space (Talairach & Tournoux, 1988); BA refers to the approximate Brodmann's area.

While this analysis showed greater activation in the directed forgetting than the color recognition task in the two left inferior frontal regions, if these regions are indeed involved in inhibition, activations in these regions should also be greater in the directed forgetting task compared to the simple recognition task, where the demands for inhibition should be minimal.

To test this idea, ANOVAs on the hemodynamic responses extracted from the two inferior frontal regions were carried out comparing activations across all three tasks in the last three runs (the four-word-list directed forgetting task vs. the two-word-list color recognition task vs. the two-word-list simple recognition task) via a 3 (three Tasks) × 8 (time points) analysis. Both the BA44 and BA45 regions showed significant effect of task, $F(2,24) = 16.08$, $p < .001$, $\eta^2_{partial} = .57$; $F(2,24) = 11.21$, $p < .001$, $\eta^2_{partial} = .48$, respectively. Unsurprisingly, both regions exhibited greater activation in the directed forgetting task than the color recognition task, $F(1,12) = 25.72$, $p < .001$, $\eta^2_{partial} = .68$ (the interaction with the quadratic effect of time, $F(1,12) = 28.92$, $p < .001$, $\eta^2_{partial} = .71$); $F(1,12) = 17.31$, $p = .001$, $\eta^2_{partial} = .59$ (the interaction with the quadratic effect of time, $F(1,12) = 23.06$, $p < .001$, $\eta^2_{partial} = .66$), respectively. Moreover, both regions also exhibited greater activation in the directed forgetting task than the simple recognition task, $F(1,12) = 30.88$, $p < .001$, $\eta^2_{partial} = .72$ (the interaction with the quadratic effect of time, $F(1,12) = 32.65$, $p < .001$, $\eta^2_{partial} = .73$); $F(1,12) = 13.85$, $p = .003$, $\eta^2_{partial} = .54$ (the interaction with the quadratic effect of time, $F(1,12) = 25.07$, $p < .001$, $\eta^2_{partial} = .68$), respectively, consistent with the roles of these regions in inhibition. The difference between the color recognition task and the simple recognition task, however, was not significant in either region, $F(1,12) = .13$, $p = .73$, $\eta^2_{partial} = .01$; $F(1,12) = 3.36$, $p = .09$, $\eta^2_{partial} = .22$, respectively. The interaction between these contrasts and the quadratic effect of time were not significant either, $F(1,12) = .02$, $p = .89$, $\eta^2_{partial} = .002$; $F(1,12) = 2.62$, $p = .13$, $\eta^2_{partial} = .18$, respectively. See Figure 3.5 for the time courses in three tasks in these two regions. The activation map is presented in Figure 8a (regions in green).

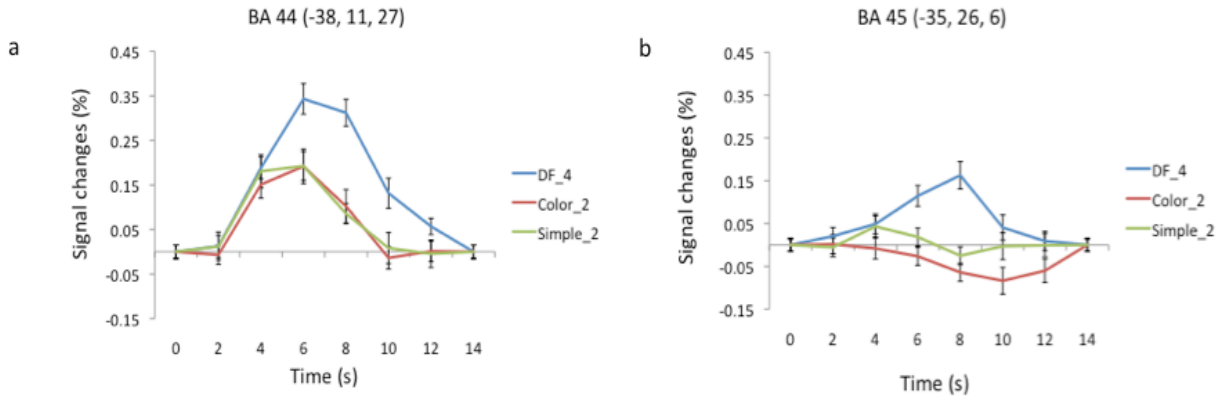

Figure 3.5. Time courses of the activation in three recognition tasks in the last three runs in the two left inferior frontal regions. DF_4: the four-word-list directed forgetting task; Color_2: the two-word-list color recognition task; Simple_2: the two-word-list simple recognition task. Error bars represented standard errors corrected for between-subject variability.

The findings from this contrast suggest that different proactive control mechanisms were involved in the directed forgetting task than in the color recognition task. The left inferior frontal regions may be involved in item inhibition that is only appropriate for the directed forgetting task but not for the color recognition task. A potential problem, however, exists in the contrast between the four-word-list directed forgetting task and two-word-list color recognition task. Although, as discussed earlier, the set sizes during retention were matched between two tasks, participants still had to encode four words in each trial in the directed forgetting task but only two words in the color recognition task. The difference in activation between these two tasks, therefore, may reflect the effect of set size during encoding instead of the difference in demand for an inhibitory function. This issue will be revisited later.

Contrast of binding. To identify regions of binding, analyses were conducted on hemodynamic signals collected from the first three runs in order to equate the hypothesized requirements for binding in the directed forgetting and color recognition tasks. Specifically, the color recognition task with four-word lists was compared with the directed forgetting task with

four-word lists. Again the errors (*d*') did not differ between these two conditions, although the response times were faster for the directed forgetting task than the color recognition task. As discussed earlier, binding is the only appropriate proactive control function in the color recognition task, while item inhibition could also be useful in the directed forgetting task. If different proactive control mechanisms are involved in the two tasks, regions involved in binding should show greater activation during the color recognition task than in the directed forgetting task. Four regions showed this pattern. One of these regions was in the left middle frontal gyrus and exhibited greater deactivation in the directed forgetting task than the color recognition task, whereas the other threes regions exhibited greater activation in the color recognition task than the directed forgetting task (i.e., the effect of binding). Importantly, among the three regions showing the effect of binding, one was in the superior parietal lobule (centered at -32, -68, 48: BA7) that has been reported by previous studies to be involved in episodic retrieval and feature binding (Nobre, Coull, Walsh, & Frith; 2003; Shafritz, Gore, & Marois, 2002). The other two regions demonstrating the effect of binding were the right putamen and the right superior occipital gyrus. Details on the regions identified in this contrast are listed in Table 3.3.

Table 3.3

Regions identified in the contrast between the four-word-list color recognition task and four-word-list directed forgetting task in the first three runs.

	Hemisphere	Coordinates (x, y, z)	BA	Name	# of Voxels
(Activation) Four-word-list color recognition task > Four-word-list directed forgetting task	Left	-32, -68, 48	7	Superior Parietal Lobule	118
	Right	23, 2, 6		Putamen	39
		41, -80, 27	19	Superior Occipital Gyrus	36

(Deactivation) Four-word-list directed forgetting task > Four-word-list color recognition task	Left	-35, 17, 54	6	Middle Frontal Gyrus	52
	Right	N/A			

Note. Coordinates are given in standardized space (Talairach & Tournoux, 1988); BA refers to the approximate Brodmann's area.

These findings showed greater activation in the superior parietal region for the color recognition task than the directed forgetting task. If this region is indeed involved in binding, its activation should also be greater in the color recognition task compared to the simple recognition task, where the demand for binding should be minimal. To determine whether activations in the superior parietal region were greater for the color recognition task than the simple recognition task, an ANOVA was carried out for the three tasks (the four-word-list directed forgetting task vs. the four-word-list color recognition task vs. the four-word-list simple recognition task) in a 3 (three tasks) × 8 (time points) analysis. The effect of Task was significant, $F(2,24) = 6.81$, $p = .01$, $\eta^2_{partial} = .36$. Contrasts between tasks showed that this region exhibited greater activation in the color recognition task than the directed forgetting task, $F(1,12) = 14.08$, $p = .003$, $\eta^2_{partial} = .54$ (the interaction with the quadratic effect of time, $F(1,12) = 8.64$, $p = .01$, $\eta^2_{partial} = .42$), and the simple recognition task, $F(1,12) = 6.24$, $p = .03$, $\eta^2_{partial} = .34$ (the interaction with the quadratic effect of time, $F(1,12) = 4.94$, $p < .05$, $\eta^2_{partial} = .29$). There was no significant difference, however, between the directed forgetting task and the simple recognition task in this region, $F(1,12) = .12$, $p = .73$, $\eta^2_{partial} = .01$ (the interaction between the contrast and the quadratic effect of time was not significant either, $F(1,12) = .45$, $p = .52$, $\eta^2_{partial} = .04$). See Figure 3.6 for the time courses in three tasks in this region. The activation map is presented in Figure 8a (regions in blue).

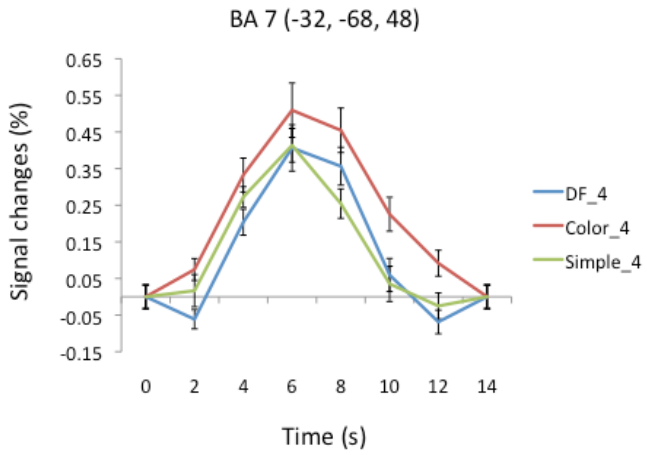

Figure 3.6. Time courses of the activation in three recognition tasks in the first three runs in the superior parietal region. DF_4: the four-word-list directed forgetting task; Color_4: the four-word-list color recognition task; Simple_4: the four-word-list simple recognition task. Error bars represented standard errors corrected for between-subject variability.

The findings from this contrast again suggest that a different proactive control mechanism was involved in the directed forgetting from the color recognition task. The left superior parietal region is involved in binding that is a proactive control mechanism engaged more greatly in the color recognition task than the directed forgetting task. However, this contrast may also be problematic because it did not match the set sizes between the two tasks during retention, although the set sizes during encoding were the same (i.e., participants were presented with four words in both tasks). In the color recognition task, participants had to maintain all four words vs. only two words in the directed forgetting task after they apply item inhibition. The regions that showed greater activation in the color recognition task than the directed forgetting task may be irrelevant to the binding function, but be involved in maintaining a larger list set.

Are these identified regions sensitive to the set size? As discussed in the previous sections, although the two contrasts identified regions involved in item inhibition and binding respectively, these effects may be confounded by the effect of set size (either during retention or

during encoding). To rule out the possibility that these identified regions were simply sensitive to a difference in set size, a conjunction analyses was conducted between the two contrasts (for individual contrasts, the activation threshold of 0.05 and cluster size of 95 voxels resulting in a corrected *p*-value of 0.1). Regions sensitive to set size should overlap, while regions specific to binding or inhibition should not overlap. The results of the conjunction are presented in Figure 3.7b. Overlapped regions that have more than 5 voxels are listed in Table 3.4.

Table 3.4

Regions overlapped between the contrast of inhibition and the contrast of binding

Hemisphere	Coordinates (x, y, z)	BA	Name	# of Voxels
Left	-6, -60, -8		Culmen	40
	-53, 5, 17	44/6	Inferior Frontal Gyrus	37
	-48, -58, 7	39	Middle Temporal Gyrus	7
	-42, 10, 26	44	Inferior Frontal Gyrus	7
Right	9, -70, 1	18	Lingual Gyrus	114
	33, 30, 29	9	Middle Frontal Gyrus	36
	1, -48, -12		Culmen	10
	44, -35, 39	40	Inferior Parietal Lobule	9
	29, 40, 29	9	Middle Frontal Gyrus	7

Note. Coordinates are given in standardized space (Talairach & Tournoux, 1988); BA refers to the approximate Brodmann's area.

Two of the overlapped regions, BA 44/6 and BA 44, were located in the left inferior frontal gyrus. The BA 44/6 region overlapped with the ventral portion of the BA 6 (precentral gyrus) region identified in the contrast of inhibition. The other overlapped region, BA 44, is a portion of the BA 44 region identified in the contrast of inhibition. These findings indicate that the BA 6 and BA 44 region identified in the contrast of inhibition may not be involved in item

inhibition per se. Rather, these regions are sensitive to memory load, and may be involved in rehearsal during encoding and retention. In contrast, the BA 45 region identified in the contrast of inhibition did not show any overlap with the regions of binding, which did not provide evidence for the assumption that this region is specific to set size. This finding is consistent with the idea that this region is specifically involved in inhibition. Moreover, no region in the superior parietal area overlapped, suggesting the superior parietal area identified in the contrast of binding is specific to binding since no evidence was found to support its sensitivity to set size.

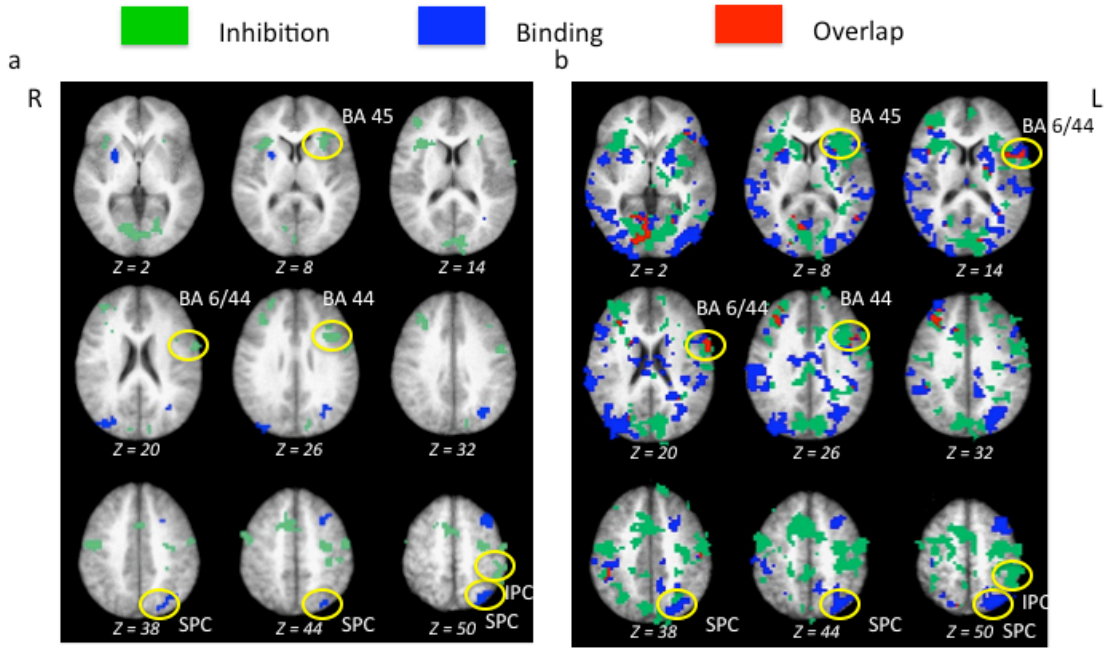

Figure 3.7. Conjunction between regions of inhibition and regions of binding. a) for individual contrasts, the activation threshold of 0.01 and cluster size of 34 voxels, resulting in a corrected *p*-value of 0.01; b) for individual contrasts, the activation threshold of 0.05 and cluster size of 95 voxels, resulting in a corrected *p*-value of 0.1. IPC: inferior parietal cortex; SPC: superior parietal cortex.

Are these identified regions involved in rehearsal? As a strategy often used in retention, rehearsal may be more involved in a more difficult task/condition than a less difficult task/condition. It is possible that the regions identified in the contrast of binding and the contrast of inhibition are involved in rehearsal, rather than the binding or inhibition processes per se. To

examine this possibility, conjunction analyses were conducted between the rehearsal regions identified in the localizer task ($p_{(uncorrected)} < 0.05$) and the contrast of binding and the contrast of inhibition (the activation threshold of 0.05 and cluster size of 95 voxels resulting in a corrected *p*-value of 0.1) respectively.

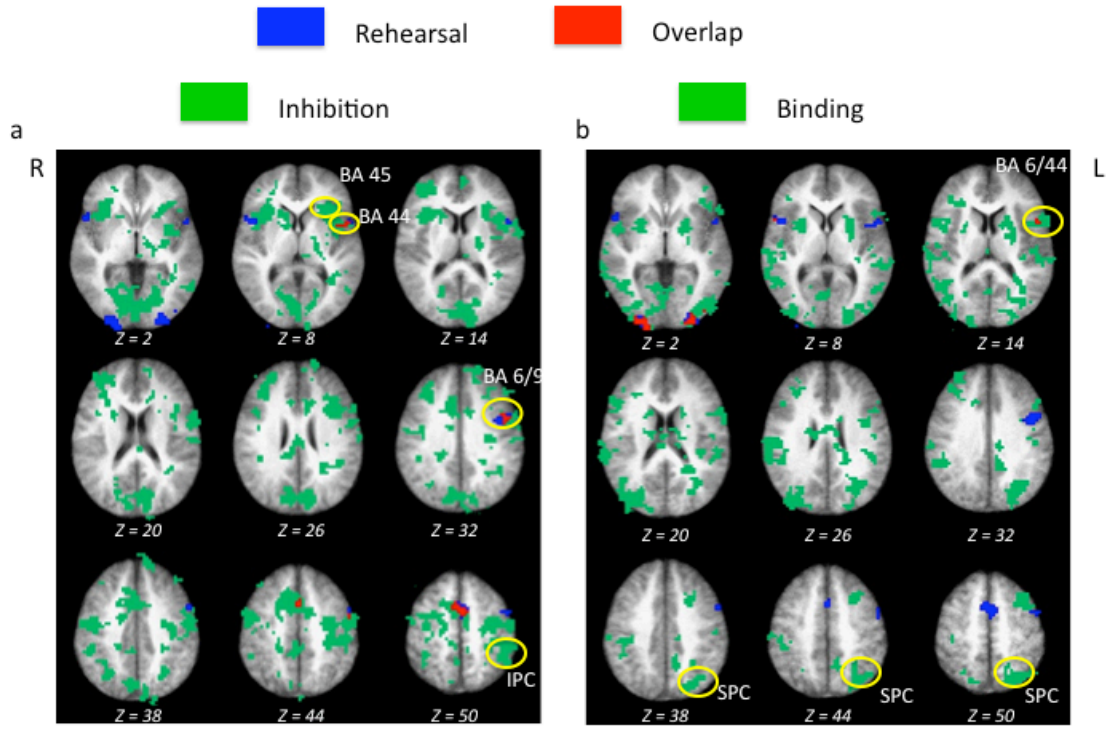

Figure 3.8. a) Conjunction between regions of inhibition and regions of rehearsal; b) conjunction between regions of binding and regions of rehearsal. IPC: inferior parietal cortex; SPC: superior parietal cortex.

The conjunction between rehearsal regions and the contrast of inhibition demonstrated three overlapped regions (> 5 voxels) two of which were located in the left frontal area. One of these two regions is in the middle/superior frontal gyrus (BA 6/9). The other located in the inferior frontal gyrus and is a portion of the BA 44 that was identified in the contrast of inhibition. However, the BA 45 region (centered at – 35, 26, 6) identified in the contrast of inhibition did not overlap with the regions of rehearsal in the left inferior frontal gyrus. These

findings are consistent with the results of the analysis on set size. That is, the BA 44 region and BA 6/9 region identified in the contrast of inhibition appear not to be specifically involved in inhibition. Importantly, though, the BA 45 region identified in the contrast of inhibition is possibly specifically involved in the inhibitory function. Detailed information on the three overlapped regions is listed in Table 3.5. The conjunction activation map is presented in Figure 3.8a.

Table 3.5

Regions overlapped between the regions of rehearsal and regions identified in the contrast of inhibition

Hemisphere	Coordinates (x, y, z)	BA	Name	# of Voxels
Left	-45, 4, 33	6/9	Inferior Frontal Gyrus	18
	-44, 6, 9	44	Inferior Frontal Gyrus	6
Right	1, -1, 55	6	Medial Frontal Gyrus	113

Note. Coordinates are given in standardized space (Talairach & Tournoux, 1988); BA refers to the approximate Brodmann's area.

The conjunction between regions of rehearsal and the contrast of binding demonstrated three overlapped regions (> 5 voxels) none of which were in the inferior frontal area or in the poster parietal area. This result did not provide evidence that the superior parietal region identified in the contrast of binding is also involved in rehearsal, suggesting that this region is specifically involved in binding. There was a slight overlapping (< 5 voxels) in BA 6/44 in the frontal cortex, again indicating these regions are sensitive to set sizes. Detailed information on the three overlapped regions is listed in Table 3.6. The conjunction activation map is presented in Figure 3.8b.

Table 3.6

Regions overlapped between the regions of rehearsal and regions identified in the contrast of binding

Hemisphere	Coordinates (x, y, z)	BA	Name	# of Voxels
Left	-28, -86, -2	18	Middle Occipital Gyrus	55
	-32, -62, -15		Declive	6
Right	25, -88, -3		Middle Occipital Gyrus	105

Note. Coordinates are given in standardized space (Talairach & Tournoux, 1988); BA refers to the approximate Brodmann's area.

Analysis of Imaging Data Following Probe Onsets (Reactive Control) in the Three Recognition Tasks

Following the onsets of probes (collapsing across all six runs that included different set sizes), whole-brain contrasts were conducted to compare intrusion negative trials and control negative trials on the mean of hemodynamic responses from the third to the fifth time points (i.e., 4-8s). Regions showing greater activation for the intrusion negative trials than for the control negative trials are involved in reactive control of proactive interference.

Reactive control in the directed forgetting task and in the color recognition task respectively. First, the interference contrast was conducted in the directed forgetting task and the color recognition task separately. Multiple comparisons were corrected by the activation threshold of 0.01 and cluster size of 34 voxels, resulting in a corrected *p*-value of 0.01. The activation map of the effect of interference in the directed forgetting task and in the color recognition task are shown in Figure 3.9a and Figure 3.9b respectively.

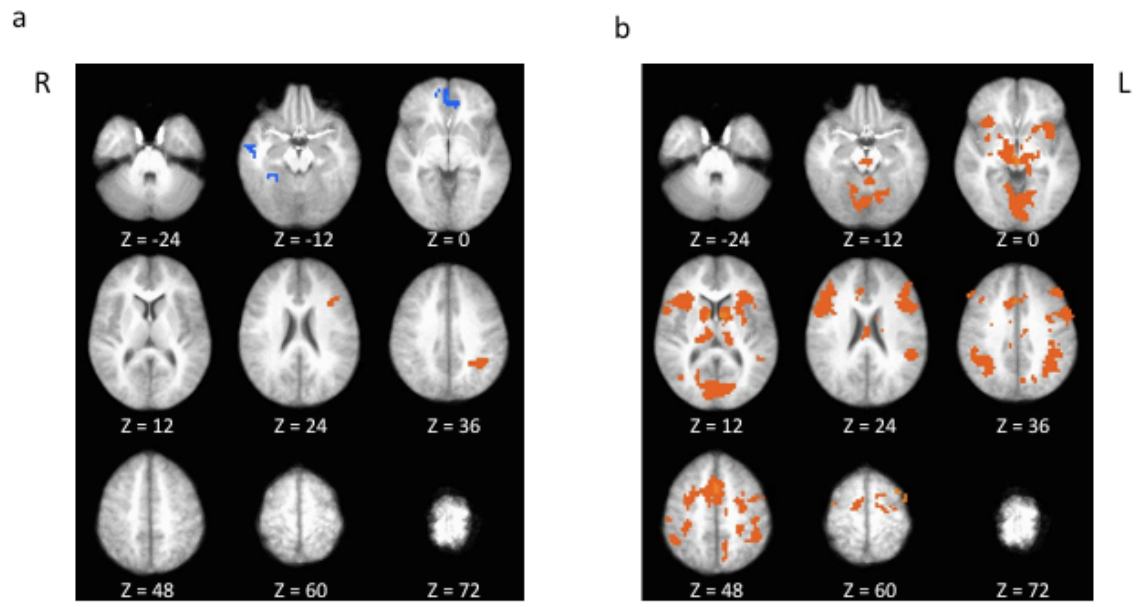

Figure 3.9. Activation maps of the interference effect in a) the directed forgetting task and b) the color recognition task. Red: intrusion condition > control condition; Blue: control condition > intrusion condition.

The activation maps for the interference effect in the two tasks demonstrated similar patterns, as left frontal and left posterior parietal regions were identified in both tasks, However, more and larger regions, including right hemisphere regions, exhibited the interference effect in the color recognition task compared to the directed forgetting task. This result is consistent with the finding in behavioral performance that the interference effect in the color recognition task was greater than that in the directed forgetting task. Signals in both tasks were combined for further analyses, and a high threshold was used due to the increased number of data points.

Reactive control combining both tasks. Combining signals in both tasks, a whole-brain contrast analysis was conducted comparing the intrusion negative trials with the control negative trials. Multiple comparisons were corrected by the activation threshold of 0.001 and cluster size of 18 voxels, resulting in a corrected *p*-value of 0.001. Then, the hemodynamic responses were extracted from each region with fixations as baselines. The quadratic contrast effect of time

(across the 7 estimated time points following the onsets of probes) was assessed in each region. Only regions exhibiting a significant quadratic effect ($p < .05$) of time and with the maximum BOLD signal exceeding |0.15| will be reported.

Nine regions were identified in this contrast. One region peaked in the left middle frontal gyrus (BA9) and extended to the inferior frontal gyrus (BA 44 & 45). In addition, regions in the bilateral inferior parietal lobule were also identified. Other regions showing greater activation for the intrusion negative condition than the control negative condition are the right insular, the cingulate gyrus, the left precentral gyrus, the declive, and the thalamus. Details on these regions are listed in Table 3.7. See Figure 3.10 for the time courses of the left frontal region and bilateral posterior parietal regions.

Table 3.7

Regions identified in the contrast between the intrusion negative trials and the control negative trials.

	Hemisphere	Peak Coordinates (x, y, z)	BA	Name	# of Voxels
(Activation) Intrusion negative > Control negative	Left	-44, 29, 30	9	Middle Frontal Gyrus	193
		-38, -56, 42	40	Inferior Parietal Lobule	91
		-41, -5, 60	6	Precentral Gyrus	61
		-2, -74, -7		Declive	25
	Right	44, -50, 45	40	Inferior Parietal Lobule	106
		35, 20, 9	13	Insula	100
		2, 17, 42	32	Cingulate	89
		5, -8, 3		Thalamus	22
		11, 20, 30	32	Cingulate	21

Note. Coordinates are given in standardized space (Talairach & Tournoux, 1988); BA refers to the approximate Brodmann's area.

Although the left frontal and bilateral posterior parietal regions showed the same activation pattern (i.e., greater activation for the intrusion negative trials than the control negative trials in the directed forgetting task and the color recognition task), they were predicted to be engaged in different functions. More specifically, the frontal region (i.e., left inferior frontal cortex) was suggested to be involved in inhibition, while the bilateral posterior parietal regions were suggested to be involved in binding. If this is the case, in the simple recognition task, these regions should demonstrate different activation patterns. The activation in the left frontal region should not differ between the positive and negative trials, since there was no greater interference in any trial type and the same degree of inhibition was needed. The activation in the bilateral posterior parietal regions, however, should exhibit greater activation for the positive trials compared to the negative trials. Since the positive probes appeared during the presentation of the lists and were written in a certain color, these probes were likely automatically linked to the colors although the linking was not required by the task. Therefore, encountering these probes could trigger retrieval of the binding relations and activate the posterior parietal regions. By contrast, the negative probes did not appear in the lists. Thus the negative probes should evoke less activation in these regions. To examine this idea, a two-way ANOVA of Probe Type (negatives vs. positive) × Region (left frontal vs. right parietal vs. left parietal) was conducted for the simple recognition task on the peak of activation (4-6s immediately following the onset of the probe). The main effect of Region was significant, $F(2,24) = 5.21$, $p = .01$, $\eta^2_{partial} = .33$. Post-hoc tests of contrasts showed that the activation was greater in the left posterior parietal region compared to the right posterior parietal region, $F(1,12) = 8.16$, $p = .01$, $\eta^2_{partial} = .41$. In addition, the activation was greater in the left frontal region compared to the right posterior

parietal region, $F(1,12) = 6.04$, $p = .03$, $\eta^2_{partial} = .34$, while the activation did not significantly different between the left frontal region and the left posterior parietal regions, $F(1, 12) = .50$, $p = .50$, $\eta^2_{partial} = .04$. More importantly, although the main effect of Probe Type was not significant, $F(1,12) = 2.84$, $p = .12$, $\eta^2_{partial} = .19$, there was significant interaction between Region and Probe Type, $F(2, 24) = 13.83$, $p < .001$, $\eta^2_{partial} = .54$. Simple effects of Probe Type were examined in each region via paired-sample *t*-tests. As predicted, the activation was significantly greater for the positive trials than the negative trials in the right posterior parietal region, $t(12) = 3.12$, $p = .01$, $d = .85$. This pattern was not significant in the left posterior parietal region, $t(12) = 1.85$, $p = .09$, $d = .51$, although the effect size was medium. More importantly, the difference between probe types in the left frontal region was not significant, $t(12) = .44$, $p = .67$, $d = .12$, suggesting that the region was involved equally for both probe types. Then, these findings are consistent with the functional dissociation between the frontal and posterior parietal regions.

In addition, in the directed forgetting and the color recognition tasks, the positive probes were also encoded with links to colors in the lists. As a result, these probes, just like the intrusion negative probes, should also evoke greater activation of the posterior parietal regions than the control negative probes, if these regions are indeed involved in binding. By contrast, the frontal region should not exhibit significantly different activation between the positive trials and the control negative trials, since no greater interference was expected for the positive trials than for the control negatives and no greater inhibition should be involved. To test these predictions, a three-way ANOVA of Task (the directed forgetting task vs. the color recognition task) × Probe Type (control negative vs. intrusion negative vs. positive) × Region (left frontal vs. right parietal vs. left parietal) was conducted on the peak of activation (4-6s immediately following the onset of the probe). The main effect of Region was significant, $F(2,24) = 4.53$, $p = .02$, $\eta^2_{partial} = .27$.

Post-hoc tests of contrasts showed again that the activation was greater in the left posterior parietal region compared to the right posterior parietal region, $F(1,12) = 8.15$, $p = .01$, $\eta^2_{partial} = .41$, while activation did not significantly differ between the left frontal region and either of the posterior parietal regions, left: $F(1,12) = 2.63$, $p = .13$, $\eta^2_{partial} = .18$; right: $F(1,12) = 2.42$, $p = .15$, $\eta^2_{partial} = .17$. In addition, the main effect of Task was also significant. The activation for the color recognition task was greater than for the directed forgetting task, $F(1,12) = 9.10$, $p = .01$, $\eta^2_{partial} = .43$. Importantly, there was a significant main effect of Probe Type, $F(2,24) = 21.89$, $p < .001$, $\eta^2_{partial} = .65$. Post-hoc tests of contrasts showed that activation was greater for the intrusion negative trials and for the positive trials compared to the control negative trials, $F(1,12) = 56.66$, $p < .001$, $\eta^2_{partial} = .83$, $F(1,12) = 17.23$, $p = .001$, $\eta^2_{partial} = .59$. Activation did not differ significantly between the intrusion negative trials and the positive trials, $F(1,12) = 1.55$, $p = .24$, $\eta^2_{partial} = .11$. The predicted interaction between Probe Type and Region, however, was not significant, $F(4,48) = 1.58$, $p = .20$, $\eta^2_{partial} = .12$. These findings are partially consistent with the predictions in that the bilateral posterior parietal regions showed greater activation for both the intrusion negative trials and the positive trials compared to the control negative trials, supporting the role of these regions in binding. However, the study failed to find the interaction between Probe Type and Region. Specifically, there was also significantly greater activation for the positive trials than the control negative trials in the left frontal region in which no such difference was predicted. Nevertheless, this result is actually consistent with the role of the left frontal region in inhibition when considering the cooperation between the frontal region and the posterior parietal regions during reactive control, which will be discussed in detail in the discussion section. In addition, the interaction between Region and Task was significant, $F(2,24) = 8.89$, $p = .001$, $\eta^2_{partial} = .42$. The effect of Task was significant in both the left frontal region,

$F(1,12) = 12.00$, $p = .02$, $\eta^2_{partial} = .40$, and the left posterior parietal region, $F(1,12) = 14.24$, $p = .003$, $\eta^2_{partial} = .54$, but not in the right posterior parietal region, $F(1,12) = 4.23$, $p = .06$, $\eta^2_{partial} = .26$, although the effect size was quite large. The difference of activation between tasks in the parietal region likely reflected that weaker binding relations were retrieved in the directed forgetting task compared to the color recognition task. This is consistent with the involvement of item inhibition during proactive control in the directed forgetting task. As a result, the binding relations were not as well maintained in the directed forgetting task compared to the color recognition task in which active maintenance of the binding relations was involved as the proactive control mechanism. The effect of task observed in the frontal region is consistent with the behavioral finding that greater PI effect arose in the color recognition task than the directed forgetting task. Greater activation of the frontal region likely reflected greater involvement of this region in directly resolving PI in the color recognition task. None of the other interaction effect in the three-way ANOVA was significant (Region × Probe Type: $F(4,48) = 1.58$, $p = .20$; Task × Probe Type: $F(2,24) = 1.45$, $p = .26$, $\eta^2_{partial} = .12$; three-way interaction: $F(4,48) = 1.21$, $p = .32$, $\eta^2_{partial} = .09$).

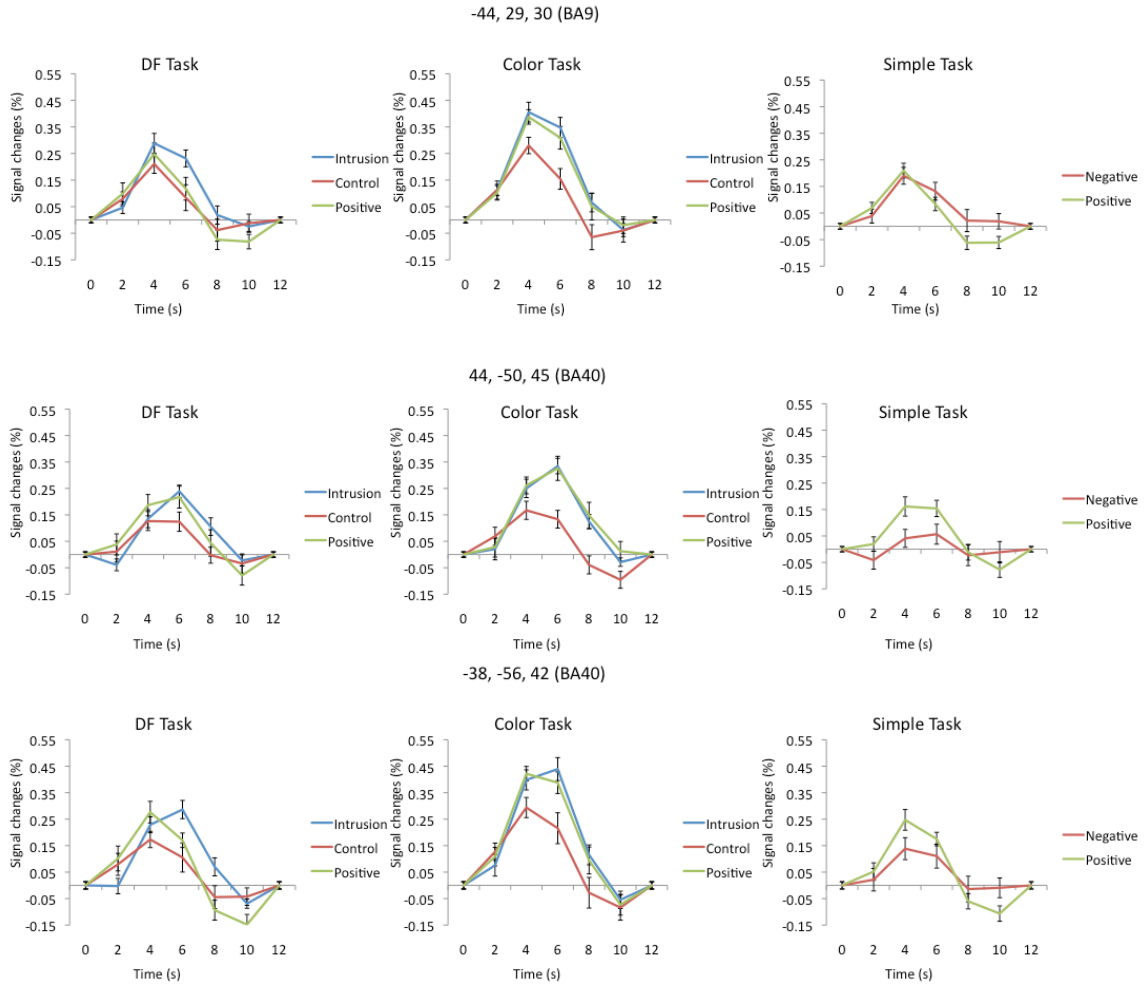

Figure 3.10. Time courses of the left frontal region and bilateral posterior parietal regions. DF task: the directed forgetting task; Color task: the color recognition task; Simple task: the simple recognition task. Error bars represented standard errors corrected for between-subject variability.

Regions of reactive control involved in inhibition. A conjunction analysis was conducted between the contrast of inhibition for proactive control (the four-word-list directed forgetting task > the two-word-list color recognition task; the activation threshold of 0.01 and cluster size of 34 voxels, resulting in a corrected *p*-value of 0.01) and the contrast of reactive control (the intrusion negative trials > the control negative trials; the activation threshold of 0.001 and cluster

size of 18 voxels, resulting in a corrected *p*-value of 0.001). If the regions of reactive control overlap with the regions of inhibition, this would suggest that these regions of reactive control are involved in the inhibitory function. The result of this conjunction demonstrated that these two contrasts overlapped (> 5 voxels) at the anterior cingulated gyrus, the left inferior frontal gyrus (BA45; BA44), and the right insula (however, the peak of hemodynamic responses of the right insula in the contrast of inhibition did not exceed |0.15|). The detailed information on these overlapped regions are listed in Table 3.8. The conjunction activation map is presented in Figure 3.11. These findings suggest that the left inferior frontal regions that are involved in reactive control are indeed engaged in the inhibitory function.

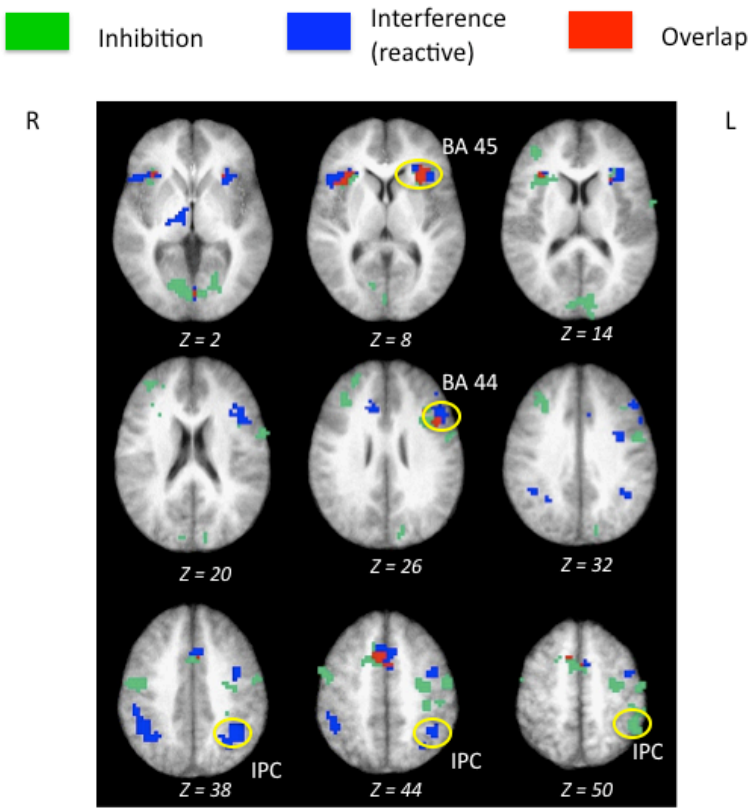

Figure 3.11. Conjunction between regions of inhibition and regions of interference effect (reactive control). IPC: inferior parietal cortex.

Table 3.8

Regions overlapped between the contrast of inhibition for proactive control and the contrast of reactive control

Hemisphere	Coordinates (x, y, z)	BA	Name	# of Voxels
Left	-5, 11, 39	32	Cingulate Gyrus	40
	-32, 26, 6	45	Inferior Frontal Gyrus	37
	-32, 14, 24	44	Inferior Frontal Gyrus	14
Right	35, 23, 3	13	Insula	37

Note. Coordinates are given in standardized space (Talairach & Tournoux, 1988); BA refers to the approximate Brodmann's area.

Regions of reactive control involved in binding. To examine whether there are regions of reactive control also involved in binding, a conjunction analysis was conducted between the contrast of binding for proactive control (the four-word-list color recognition task > the four-word-list directed forgetting task; the activation threshold of 0.01 and cluster size of 34 voxels, resulting in a corrected *p*-value of 0.01) and the contrast of reactive control (the activation threshold of 0.001 and cluster size of 18 voxels, resulting in a corrected *p*-value of 0.001). If the regions of reactive control overlap with the regions of binding, such would suggest that these regions of reactive control are involved in the binding function. This analysis, however, did not identify any overlapped region with more than five voxels, although a small overlap (< five voxels) was found in the posterior parietal area (see Figure 3.12a). Therefore a lower threshold (the activation threshold of 0.01 and cluster size of 34 voxels, resulting in a corrected *p*-value of 0.01) was applied to the contrast of reactive control for another conjunction analysis to examine whether these two regions overlap at all. This analysis identified one overlapped region with seven voxels in the left inferior parietal gyrus (centered at -32, -63, 39; see Figure 3.12b). This analysis showed that a portion of the posterior parietal region involved in reactive control is also

engaged in the binding function. The binding function for reactive control, however, may involve somewhat different mechanism from the binding function for proactive control, given that a large portion of the posterior parietal region identified for reactive control did not overlap with the posterior parietal region identified for proactive control.

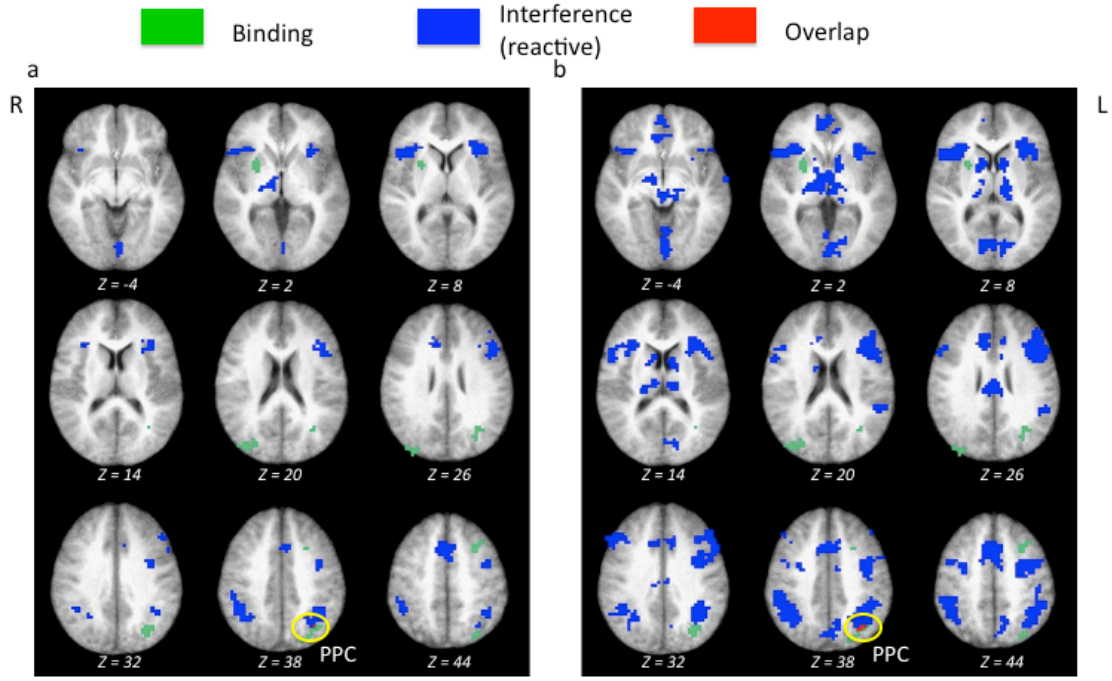

Figure 3.12. Conjunction between regions of binding and regions of interference effect (reactive control). a) for the contrast of interference effect (reactive control), the activation threshold of 0.001 and cluster size of 18 voxels, resulting in a corrected *p*-value of 0.001; b) for the contrast of interference effect (reactive control), the activation threshold of 0.01 and cluster size of 34 voxels, resulting in a corrected *p*-value of 0.01. PPC: posterior parietal cortex.

The Role of Hippocampus in Encoding and Retrieval

Since some recent studies have reported a role of the hippocampus in WM tasks (Nee et al., 2007; Oztekin, Davachi, & McElree, 2010), a post-hoc analysis of the activation in bilateral hippocampus was conducted. A low activation threshold $p_{\text{uncorrected}} < .05$ and a criteria of at least five voxels was used since a prior interest was focused on the hippocampus areas. The hippocampus should be more activated when more information is encoded or maintained (the

process reflected by signals immediately following the list onsets). In addition, the hippocampus should be more activated for familiar items compared to new items during retrieval (the process reflected by signals immediately following the probe onsets).

Signal immediately following the list onsets (encoding). Regions in bilateral hippocampus that demonstrated a significant main effect of condition (six conditions including three tasks in the first vs. the last three runs), $p_{\text{uncorrected}} < .05$, were identified as regions involved in encoding and retention. Only one region larger than five voxels was identified (centered at -34, -19, -13; 12 voxels).

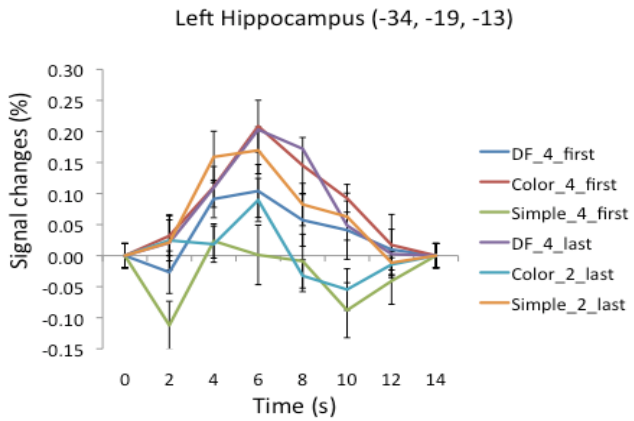

Figure 3.13. Time courses of the activation in three recognition tasks in the first and last three runs in the left hippocampus. DF_4_first: the four-word-list directed forgetting task in the first three runs; Color_4_first: the four-word-list color recognition task in the first three runs; Simple_4_first: the four-word-list simple recognition task in the first three runs. DF_4_last: the four-word-list directed forgetting task in the last three runs; Color_2_last: the two-word-list color recognition task in the last three runs; Simple_2_first: the two-word-list simple recognition task in the last three runs. Error bars represented standard errors corrected for between-subject variability.

Then hemodynamic responses in this region were extracted for all six conditions (see Figure 3.13). Two-way repeated measures ANOVAs of Task (the directed forgetting task vs. the color recognition task) × Time Point (eight) were conducted between two tasks in each of a set of comparisons. For signals collected from the first three runs, first, the activation for the four-word-list directed forgetting task did not significantly differ from the activation for the four-

word-list color recognition task (the interaction between Task and Time Point, $F(1,12) = 3.10$, $p = .10$, $\eta^2_{partial} = .21$). If item inhibition reducing the set size is involved in the directed forgetting task, such an idea predicts a smaller activation in the hippocampus in the directed forgetting task compared to the color recognition task. The failure to find a difference between the two tasks may be due to the inefficient item inhibitory function. That is, item inhibition did not perfectly delete irrelevant items in the directed forgetting task. However, both the four-word-list directed forgetting task and the four-word-list color recognition task evoked greater activation than the four-word-list simple recognition task (the interaction between Task and Time Point, the four-word-list directed forgetting task: $F(1,12) = 8.57$, $p = .01$, $\eta^2_{partial} = .42$; the four-word-list directed forgetting task: $F(1,12) = 15.84$, $p = .002$, $\eta^2_{partial} = .57$). These findings are consistent with the idea that no binding relations needed to be encoded and maintained in the simple recognition task.

For signals collected from the last three runs, the activation for the four-word-list directed forgetting task was greater than the activation for the two-word-list color recognition task (the interaction between Task and Time Point, $F(1,12) = 8.61$, $p = .01$, $\eta^2_{partial} = .42$), consistent with the idea that more words needed to be encoded in the directed forgetting task compared to the color recognition task. The activation in the four-word-list directed forgetting task, however, did not significantly differ from the activation in the two-word-list simple recognition task (the interaction between Task and Time Point, $F(1,12) = .58$, $p = .46$, $\eta^2_{partial} = .05$). Given that the set size was bigger in the directed forgetting task compared to the simple recognition task, such a finding is difficult to explain when attributing the role of the hippocampus to encoding in WM. In addition, the two-word-list simple recognition task evoked greater activation than the two-word-list color recognition task (the interaction between Task and Time Point, $F(1,12) = 12.36$, p

= .004, $\eta^2_{partial}$ = .51). Such a finding is inconsistent with the prediction that more activation should be observed in the color recognition task than in the simple recognition task, since binding relations needed to be encoded in the color recognition task but not in the other task.

Signal immediately following the probe onsets (retrieval). Regions in bilateral hippocampus that demonstrated a significant main effect of condition, $p_{\text{uncorrected}} < .05$, were identified as ROIs during encoding. The eight conditions including three probe types (control negative vs. intrusion negative vs. positive) in the directed forgetting task and the color recognition task and two probe types (negative vs. positive) in the simple recognition task. There were two regions with more than five voxels (centered at -28, -19, -11, 16 voxels; centered at 29, -16, -13, 15 voxels). However, neither region demonstrated a maximum BOLD signal exceeding |0.15|.

Discussion

This fMRI study investigated the neural basis and mechanisms of proactive control and reactive control in PI resolution, particularly focusing on control in a directed forgetting task relative to a color recognition task. Proactive control and reactive control were examined separately by analyzing hemodynamic signals immediately following the onsets of lists and following the onsets of probes, respectively. Moreover, whether item inhibition or binding is involved in proactive control in the directed forgetting task was examined by comparing the two tasks. In addition, whether episodic inhibition or familiarity inhibition is involved in reactive control was examined by conjunction analyses between regions of reactive control and regions of inhibition/binding identified for proactive control.

Performance on the Three Recognition Tasks.

Participants' performance in both response times and accuracy were better in the simple

recognition task compared to the other two tasks. These findings are consistent with the fact that the simple recognition task demands only a response to the familiarity of items, while the other two tasks required judgments based on associations between items and colors.

Moreover, participants responded faster in the directed forgetting task than the color recognition task, even though in the last three runs the lists in the directed forgetting task had a larger set size (i.e., four-word set) than the color recognition task (i.e., two-word set). This finding cannot be explained by response bias since there were the same proportions of negative and positive trials in the two tasks. Since the color recognition task had an average set size of three while the directed forgetting task had a set size of four across all runs, if the two tasks involved the same proactive control mechanism (i.e., binding), performance on the color recognition task should have been better than the directed forgetting task. This prediction, however, is opposite to the findings of the present study. Therefore, our findings suggest that different processes are involved in these two tasks. More specifically, item inhibition was involved in the directed forgetting task during the retention interval while binding was involved in the color recognition task. Since item inhibition eliminated the irrelevant items, participants could reply more on the familiarity level of the probe in making judgments in the directed forgetting task. Thus, the directed forgetting task was easier compared to the color recognition task in which participants had to respond based on the recollection of the association between items and colors. In contrast, if binding was the only mechanism involved in the directed forgetting task, participants would have to first retrieve the binding relations between all items and their colors exactly as they would do in the color recognition task, and then determine the relevant items (i.e., those written in the cued color). Thus, they should not have performed faster and more accurately in the directed forgetting task compared to the color recognition task.

Furthermore, the faster response times in the directed forgetting task is also consistent with the idea of item inhibition in terms of the set size. That is, only half of the list (i.e., the relevant items) needs to be remembered after inhibiting the irrelevant items. The memory load in the directed forgetting task, therefore, is smaller than that in the color recognition task in which the whole list needs to be remembered.

Second, the proactive interference effects were replicated in the behavioral results for the directed forgetting task and the color recognition task. In both the response times and accuracy, participants showed more difficulty rejecting the intrusion negative trials than the control negative trials in the directed forgetting task and in the color recognition task. More importantly, the PI effect was greater in the color recognition task than the directed forgetting task in response times, suggesting that item inhibition involved in proactive control in the directed forgetting task was more efficient in resolving PI.

Neural Basis.

Proactive control. The neural basis of proactive control was examined on hemodynamic signals following the onsets of lists. These signals were separated from signals driven by probe recognitions (i.e., reactive control) by jittered delay intervals between the color cues and the probes.

Regions of inhibition were identified in the contrast between the four-word-list directed forgetting task and the two-word-list color recognition task. This contrast was termed the contrast of inhibition. Both tasks were from the last three runs. Therefore, the difference observed between tasks was not due to fluctuation of signals across runs. Because item inhibition could only be useful in the directed forgetting task while binding is required in the color recognition task, regions that are involved in item inhibition should exhibit greater activation in

the directed forgetting task than the color recognition task. This activation pattern was termed the effect of inhibition. Although the set sizes of the two tasks in this contrast were different (four-word lists in the directed forgetting task vs. two-word lists in the color recognition task), it needs to be noted that the memory loads during retention were matched. If item inhibition is indeed involved in the directed forgetting task, only half of the list (i.e., two words) need to be remembered in each trial, whereas binding in the color recognition task requires maintenance of the whole list (i.e., two words as well).

In contrast, regions of binding were identified in the contrast between the four-word-list color recognition task and the four-word-list directed forgetting task. This contrast was termed the contrast of binding. Both tasks were from the first three runs. Because binding is only required in the color recognition task but not in the directed forgetting task, if different control mechanisms are involved in the two tasks, regions that are involved in binding should exhibit greater activation in the color recognition task than the directed forgetting task. This activation pattern was termed the effect of binding. The set sizes during encoding were matched in this contrast (both tasks had four-word lists), but there was a bigger set size during retention in the four-word-list color recognition task than the four-word-list directed forgetting task (only half of the list needs to be remembered after inhibiting irrelevant items).

Since both contrasts were confounded with the effect of set size (difference in set size during encoding in the contrast of inhibition; difference in set size during retention in the contrast of binding), a conjunction analysis was also conducted between these two contrasts. Regions identified in the two contrasts that are sensitive to set size should overlap between the two contrasts.

Regions of inhibition. Three regions in the left frontal cortex (BA 44; BA 45; BA 6/9)

showed the effect of inhibition. Two of these regions (BA 44 & BA 6/9), however, may not be involved in item inhibition per se. The left BA 44 region has been found to be involved in rehearsal (Ravizza et al., 2004; Smith & Jonides, 1998). In the present study, this region is possibly engaged in more intensive rehearsal in the four-word-list directed forgetting task than the two-word-list color recognition task, since there were four words in the list that needed to be encoded in the directed forgetting task while only two in the color recognition task. Evidence for its roles in rehearsal is that these regions also exhibited greater activation in the contrast of binding, presumably due to the greater memory load during retention in the four-word-list color recognition task than the four-word-list directed forgetting task. Furthermore, the BA 44 region also partially overlapped with the regions identified in the rehearsal localizer task. The other prefrontal region BA 6/9 has been found to play a role in spatial WM (Nee et al., 2012). The finding that this region showed the set size effect may be caused by the fact that more spatial information needed to be encoded or maintained for the larger set size. As discussed in the individual differences study, since words in the lists were presented simultaneously at different locations, participants could use the spatial information to build item-context association (i.e., the binding process) and identify irrelevant item to inhibit (i.e., the item inhibitory process). The involvement of spatial WM is consistent with the findings in the individual differences study. That is, binding measured in tasks involving spatial information and inhibition measured in the saccade-antisaccade task predicted PI resolution. In contrast, the other left frontal region (BA 45) did not show the effect of binding. It is possible that this region is not sensitive to set size. Moreover, it did not overlap with the regions involved in rehearsal. Therefore, this region is possibly a region specifically involved in the function of item inhibition. A meta-analysis study found that the mid-lateral prefrontal area is sensitive to verbal content and very reliably involved

in resisting memory intrusions (Nee at al., 2012).

Besides these left frontal regions mentioned above, some other regions also showed the effect of inhibition. The left postcentral gyrus and right precental gyrus may be involved in sub-vocal rehearsal of the larger word set during encoding in the four-word-list directed forgetting task compared to the two-word-list color recognition task. The lingual gyrus may be responsible for visual processing of the larger word set in the directed forgetting task. In addition, a region in the left inferior parietal area also exhibited the effect of inhibition. This region, however, did not overlap with any regions that showed greater activation in the four-word-list color recognition task than the four-word-list directed forgetting task (i.e., the contrast of binding), suggesting it is not involved in the binding function although the parietal cortex is expected to be. By contrast, some previous studies attributed the function of the inferior parietal lobule to the process of converting spelling-to-sound in reading (Bookheimer, Zeffiro, Blaxton, Gaillard, & Theodore, 1995; Horwitz, Rumsey, & Donohu, 1998; Pugh et al., 2000; Shaywitz et al., 2002; Stoeckel, Gough, Watkins, & Devlin, 2009). This function is consistent with the fact that the list size is larger in the directed forgetting task (i.e., four words) than the color recognition task (i.e., two words) in the contrast of inhibition. Another region that showed the effect of inhibition is the anterior cingulate cortex. This area has often been reported to be activated in tasks involving conflicts and inhibition, such as the flanker task, Stroop task and reactive PI resolution (Badre & Wagner, 2004; Carter & van Veen, 2007; Milham et al., 2001; Nelson, Reuter-Lorenz, Sylvester, Jonides, & Smith, 2003; van Veen, Cohen, Botvinick, Stenger, & Carter, 2001; van Veen & Carter, 2005; Weissman, Giesbresht, Song, Mangun, & Woldorff, 2003).

Regions of binding. As predicted, a region in the left superior parietal lobule exhibited the effect of binding. This region did not overlap with the regions identified in the contrast of

inhibition or the regions identified in the rehearsal localizer task. Therefore, it is possibly a region specifically involved in the binding function.

Another region that exhibited the effect of binding is the right superior occipital gyrus that might be involved in mental imagery that was perhaps engaged to maintain binding relations between colors and items (Mellet et al., 1996; Lambert, Sampaio, Mauss, & Scheiber, 2004).

Reactive control. Regions involved in reactive control were examined on the hemodynamic signals following the onsets of the probes. These regions should show greater activation for the intrusion negative trials compared to the control negative trials. This activation pattern was termed the effect of interference. Since similar regions showed the effect of interference in the directed forgetting task and in the color recognition task (specifically both regions in the left inferior frontal gyrus and regions in the posterior parietal lobule exhibited the effect of interference in both tasks), the two tasks were combined and an overall contrast between the intrusion negative trials and the control negative trials was conducted. Then, to determine the functions of the regions exhibiting the effect of interference, these regions were overlapped with regions exhibiting the effect of inhibition and binding for proactive control.

Regions of reactive control involved in inhibition. First, a large region in the left frontal cortex covering the middle frontal gyrus (BA 9) and the inferior frontal gyrus (BA 44 & 45) showed the effect of interference. The repeated measures ANOVA showed that this region did not exhibit greater activation for the positive trials than the negative trials in the simple recognition task. This finding is consistent with the role of this region in inhibition, given that a similar degree of interference and demand on inhibition was engaged between the positive trials and the negative trials. Importantly, based on the conjunction analysis, the BA 44 and BA 45 portion of this region overlapped with the regions exhibiting the effect of inhibition for proactive

control. These findings suggest that at least a portion of this left frontal region is involved in inhibition.

Regions of reactive control involved in binding. Interestingly, bilateral inferior parietal areas that were predicted to be involved in the binding function were also more activated for the intrusion negative trials than the control negative trials. The repeated measures ANOVA showed that these regions exhibited greater activation for the positive trials than the negative trials in the simple recognition task, and exhibited greater activation for the positive trials than the control negative trials in the directed forgetting task and the color recognition task. These findings are consistent with the role of these regions in binding, since the positive probes trigger retrieval of binding relations between them and their colors in the list while the control negative/negative probes did not appear in the lists and had no binding relations. Furthermore, according to the conjunction analyses, this region does not overlap with the inferior parietal region identified in the contrast of inhibition, suggesting they carried out different functions. The inferior parietal region identified in the contrast of inhibition was suggested to be involved in visual word processing rather than binding. In contrast, the inferior parietal region involved in reactive control was adjacent and slightly overlapped with the superior parietal region exhibiting the effect of binding for proactive control, suggesting that at least a portion of the inferior parietal region involved in reactive control was engaged in the binding function.

Other regions. Other regions that were involved in reactive control are the the right insula, the anterior cingulate cortex, and the thalamus. The anterior cingulate overlapped with the region that exhibited the effect of inhibition for proactive control. This region has been suggested to be involved in conflict detection (e.g., Carter & van Veen, 2007). The thalamus has been long known to play a crucial role in episodic memory (e.g., Aggleton & Brown, 1999; Cipolotti et al.,

2008; Graff-Radford, Tranel, Van Hoesen, & Brandt, 1990; Mayes, Daum, Markowisch, & Sauter, 1997). As for the right insula, although it has been considered to be an area responsible for emotion and self-relevant feeling (e.g., Janig & Habler, Craig, 2002), activation of this region has also been reported in cognitive control tasks devoid of emotion (Braver et al., 2010; Wager & Smith, 2003). Wager and Barrett (2004) suggested that the insula might be involved in a process that is engaged in both affective tasks and cognitive control tasks. That is, these tasks require motivated decision making in goal formation, updating task goal based on affective information, and affective error detection.

In addition, the involvement of the hippocampus in WM tasks was reported by some recent studies (Nee et al., 2007, 2011; Oztekin et al., 2010). The findings of this study, however, were not entirely consistent with these previous studies. First, during encoding the two-word-list simple recognition task evoked greater activation in the left hippocampus than the two-word-list color recognition task, inconsistent with the idea that more binding relations needed to be encoded in the color recognition task than the simple recognition task. In addition, the study failed to find any activation difference between the two-word-list simple recognition task and the four-word-list directed forgetting task. Given the low threshold and small voxel size of the hippocampus region identified in this study, it is possible that the activation found in the hippocampus was noise. Moreover, no region in the hippocampus was found to be involved in retrieval. The role of the hippocampus in WM needs to be further examined by future studies.

Functions of the frontal regions. Multiple areas of the frontal regions, particularly the left frontal area (i.e., BA 45, BA 44, BA 9, BA 6), were identified in various contrasts in this study. As discussed earlier, based on the conjunction analyses on the effect of set size and the effect of rehearsal, the inferior frontal region BA 44, the middle frontal region BA 9 and pre-

motor region BA 6 were also involved in the rehearsal tasks. The activation of these regions was also found in many studies on rehearsal, working memory, and PI tasks (e.g., Awh, Smith, & Jonides, 1995; Badre & Wagner, 2005; Baldo & Dronkers, 2006; Nee et al., 2007, 2012). In contrast, the BA 45 region is possibly specifically involved in the inhibitory function for both proactive control and reactive control, since the study failed to find evidence that this region was sensitive to set size or involved in rehearsal. This finding is consistent with results from previous studies. For proactive control, a left BA 45/46 region was found to be more engaged in the PI task with a high-proportion of interfering trials (promoting proactive control) compared to the PI task with a low-proportion of interfering trials (promoting reactive control) (Burgess et al., 2010). In addition, consistent with the idea that the BA 45 region is responsible for inhibiting irrelevant items as a proactive control mechanism in the directed forgetting task, Anderson et al. (2004) reported that the bilateral BA 45/46 area (stronger in the left) played a role in suppressing unwanted memory. For reactive control, the left BA 45 region has been repeatedly found to be more activated for interfering trials relative to control trials in PI resolution, in addition to more superior frontal areas (e.g., BA 44/9) that might be involved in rehearsal (Badre & Wagner, 2005; Nee et al., 2007).

Another question that needs to be addressed is the nature of the inhibitory functions involved in these regions. Munakata et al. (2011) proposed two inhibitory effects produced by the prefrontal cortex. One is a direct inhibitory effect. To produce this effect, the prefrontal cortex activates inhibitory GABAergic interneurons in the target cortex and globally shuts down the function of the target cortex. One example of the direct inhibitory function is response inhibition. The prefrontal sends signals to the subthalamic nucleus which provides global inhibition over the output of the basal ganglia and pauses motor output (Aron, 2007; Frank,

Samanta, Moustafa, & Sherman, 2007). The other inhibitory effect is an indirect competitive inhibition. In this type of inhibition, instead of telling the target area "Do not do X", the prefrontal cortex represents the abstract task goal and sends a "Do Y" command. In other words, rather than directly inhibiting the inappropriate representation or function, the prefrontal cortex helps the targets eventually winner of the competition by promoting these goals. In terms of how the enhancement of targets would resolve the competition, computational models have proposed different mechanisms, such as lateral inhibition between alternative choices (Howard et al., 2006) or the involvement of a "booster" mechanism which serves to amplify differences in the activation of alternative choices until a difference threshold is reached (Oppenheim et al., 2009). Since we did not observe a reduction in activation in any region due to the engagement of the inferior frontal gyrus, the direct inhibitory function may not play a role in PI resolution. Instead, competitive selection is achieved by an indirect inhibitory function promoting target representations.

Functions of the posterior parietal regions. Three posterior parietal regions were identified in difference contrasts. One region in the superior parietal lobule showed greater activation in the color recognition task compared to the directed forgetting task (i.e., the effect of binding). Regions in the bilateral dorsal inferior parietal lobule showed greater activation for the intrusion negative trials than the control negative trials (i.e., the effect of interference). One region in the left inferior parietal lobule that is anterior and ventral to the dorsal inferior parietal lobule exhibiting the effect of interference is more activated in the four-word-list directed forgetting task relative to the two-word-list color recognition task (i.e., the effect of inhibition).

Among these three regions, the region exhibiting the effect of inhibition did not overlap with any of the other two regions, suggesting that this region is not involved in either reactive

control or binding. In addition, this region (in the supramaginal gyrus) has been suggested to play a role in phonological encoding during word processing (Bookheimer et al., 1995; Horwitz et al., 1998; Pugh et al., 2000; Shaywitz et al., 2002; Stoeckel et al., 2009; Ravizza et al., 2004). This region was more activated perhaps because there was a higher demand on word encoding in the four-word-list directed forgetting task compared to the two-word-list color recognition task.

The other two posterior parietal regions (i.e., the superior parietal lobule in the contrast of binding and the dorsal inferior parietal lobule in the contrast of interference for reactive control), however, did show a slight overlap, indicating at least a portion of these two regions are involved in the same function. As for the superior parietal lobule, it was likely involved in linking and maintaining the association between items and their ink colors because it exhibited the effect of binding, and was not sensitive to set size. This idea is supported by prior evidence indicating that the superior parietal gyrus was more engaged in a feature binding task than in single feature tasks (Shafritz et al., 2002) and this region played a role in episodic memory (Cabeza et al., 2008; Uncapher & Wagner, 2009; Wagner et al., 2005). For the dorsal inferior parietal region, the finding from this region replicated the results of previous studies examining reactive control in PI tasks (Badre & Wagner, 2005; Nee et al., 2007). Although many studies have suggested that this region is a storage site for phonological information (Awh et al., 1995; Baldo & Dronkers, 2006; Becker, MacAndrew, Fiez, 1999; Paulesu, Frith, & Frackowiak, 1993), Ravizza et al. (2004) suggested that this region is involved in a domain-general executive control function, more particularly, focusing attention on information in working memory. In their study, this region did not exhibit any difference between verbal and nonverbal n-back tasks. This idea is in line with the finding that the inferior parietal region showed some overlap with the superior parietal region involved in binding. Evidence suggested that the role of the posterior parietal in

binding was not to store the actual binding relationships, but to shift and focus attention on integrating features from different perspectives. For example, greater parietal activation was observed when the task was asking "what and where" questions compared to "what only" questions, regardless whether participants' responded to the question correctly or not (Dobbins, Foley, Schacter, & Wagner, 2002; Dobbins, Rice, Wagner, Schacter, 2003; Dobbins & Wagner, 2005). Indeed, the lateral parietal cortex has traditionally been considered to support attention and multisensory integration (Corbetta & Shulman, 2002; Danckert & Ferber, 2006; Driver & Vuilleumier, 2001; Posner & Petersen, 1990; Vallar, 1998). More interestingly, Corbetta & Shulman (2002) proposed a model to distinguish the role of the superior parietal lobule and the inferior parietal lobule in attention. This distinction seems to be able to explain the somewhat distinct parietal regions involved in proactive and reactive control (the superior parietal for proactive control vs. the inferior parietal for reactive control). According to this model, the superior parietal lobule is engaged in top-down direction of attention, whereas the inferior parietal lobule is responsible for bottom-up capture of attention. Specifically, the superior parietal lobule prepares and orients attention voluntarily on task-relevant information based on task goals. In contrast, the inferior parietal lobule responds to reflexive attention shifts. For example, in one study, activity in the superior parietal lobule was observed during a search period, whereas the inferior parietal lobule activated more than the superior parietal lobule when a target was detected (Corbetta, Kincade, Ollinger, McAyoy, & Shulman, 2000). Because for proactive control participants needed to voluntarily drive their attention to the binding relationships, the superior parietal lobule was involved. In contrast, for reactive control, the binding relationships (appropriate and inappropriate binding) associated with the intrusion probes came to mind automatically since they were encoded and maintained during retention.

The inferior parietal lobule, therefore, was activated for reactive control.

Implications for the Hypothesized Dual-Mechanism Models.

Since proactive control and reactive control were both examined, this study was able to provide evidence for the existence of distinct proactive and reactive control mechanisms (as proposed by the dual-mechanism models of PI resolution). In addition, since regions of inhibition and regions of binding were identified by manipulating demands for these functions in different recognition tasks, the particular functions that were involved in proactive control and reactive control respectively could be addressed. The conclusions are summarized below.

First, for proactive control, item inhibition is involved in the directed forgetting task. For reactive control, regions that were specifically engaged in inhibition and binding were both involved, suggesting the inhibitory function in reactive control does not simply inhibit an inappropriate response tendency (as proposed by the familiarity inhibition account). Rather, the inhibitory function acts upon the incorrectly encoded binding relations (as proposed by the episodic inhibition account).

The results, therefore, suggest that in the commonly used PI task – the directed forgetting task - item inhibition is involved in proactive control while episodic inhibition is involved in reactive control. These findings, however, are consistent with neither the dual inhibition model (assuming item inhibition as proactive control and familiarity inhibition as reactive control) nor the binding-episodic inhibition model (assuming binding as proactive control and episodic inhibition as reactive control). So a new dual mechanism model needs to be proposed in which item inhibition and episodic inhibition work together to resolve PI. First, binding relationships between items and ink colors have to be encoded during list presentations. Otherwise the item inhibition function would not "know" which items are irrelevant and need to be inhibited. The

reason that no region involved in binding was identified in the contrasts of proactive control is that these contrasts compared the directed forgetting task to the color recognition task, but both tasks require the encoding of binding relationships. However, since the items in different colors are presented simultaneously, items are weakly associated with the inappropriate color although they have a stronger link with the color they were actually presented in. The appropriate links between the irrelevant items and the irrelevant color, however, are strong enough to guide the inhibitory function to act on irrelevant items, since the forgetting cues come up soon after the presentations of the lists and the memory of binding relationships have not decayed very much. Then when the probe is presented, one might assume that the item inhibitory function is useful in resolving PI because recognition involves both familiarity and search (which involves the retrieval of contextual cues) (Atkinson et al., 1974; also see Mandler, 1980; Jacoby, 1991). For the intrusion negative trials, since the irrelevant items (i.e., the intrusion negatives) were deleted from memory, they are less familiar and a negative response can be generated on the basis of familiarity. At the same time, the search process will attempt to retrieve the color that was associated with the intrusion negatives. Although each item in the list has a stronger association with its correct color and a weaker association with the incorrect color, the correct association will have greatly decayed during the retention interval; thus, retrieval of the appropriate association suffers from interference. Because of this interference, episodic inhibition needs to be involved to suppress the inappropriate links so that the appropriate color can be retrieved. Here an important assumption which needs to be made is that familiarity influences search - in particular, it influences episodic inhibition. When the response generated by familiarity is consistent with the direction of difference between binding strengths of appropriate and inappropriate bindings, less episodic inhibition is required. For example, when an intrusion

negative has a low level of familiarity (corresponds to a negative response), a lower threshold is required to retrieve its appropriate color (corresponds to a negative response as well because the color of a negative in the list was not the cued color). In contrast, when the response generated by familiarity is inconsistent with the direction of difference between binding strengths, more episodic inhibition is required. For example, when item inhibition did not successfully reduce the level of familiarity of an intrusion negative (leading towards a positive response), a higher threshold is required to retrieve its appropriate color (leading towards the correct negative response). In this manner, PI can be revolved by item inhibition for proactive control and episodic inhibition for reactive control. In addition, for the positive probes, interference also exists because every item in the list has a stronger appropriate association and a weaker inappropriate association with the colors. Therefore, the left frontal region involved in episodic inhibition may also be engaged in reactive control for positive probes, which is consistent with the results of the present study. However, the activation in the region of inhibition should be less for the positive probes compared to the intrusion negative probes, since the positive probes more often have a high level of familiarity that facilitates the retrieval of their appropriate color that also leads to a positive response.

In conclusion, the findings of this study suggest that item inhibition carried out by the left inferior frontal cortex (in particular, the left BA45) is involved in proactive control of PI resolution, and episodic inhibition involving the same region of inhibition (the left BA45) and bilateral posterior parietal cortex is the mechanism of reactive control.

Chapter 4. General Discussion

4.1. Summary of Findings

The goal of this thesis was to examine the mechanisms of PI resolution - specifically, to address whether distinct proactive and reactive control mechanisms indeed exist in PI resolution. If distinct proactive and reactive control mechanisms exist, then the question can be asked regarding which function (i.e., item inhibition or binding) is involved in proactive control and which function (i.e., familiarity inhibition or episodic inhibition) is involved in reactive control. Finally, one can ask whether these mechanisms play a role in the relation between PI resolution and WM.

4.1.1. The individual differences study. Individuals' performance in a standard recognition paradigm often used to tap PI resolution was measured in two versions, each of which encouraged the use of proactive control or reactive control. In addition, individuals' inhibition and binding ability was also measured in tasks that had minimal memory requirements. Moreover, WM capacity was measured in complex span tasks. To control for individuals' ability of storage and processing, their performance in short-term memory tasks was also measured.

The comparison of two sets of confirmatory factor analyses failed to provide evidence for dissociable proactive control and reactive control in the two versions of the PI tasks (i.e., the PI tasks with a large proportion of interfering trials vs. the PI tasks with a small proportion of interfering trials). However, binding and inhibition were found to be dissociable attentional control mechanisms since each of them demonstrated a unique contribution to PI resolution when the other mechanism was controlled for.

As for the mechanism of WM, individuals' performance in both binding and inhibition predicted WM capacity. In addition, PI resolution was correlated with WM capacity. However, the relation between PI and WM disappeared when controlling for binding and inhibition, suggesting that binding and inhibition are involved in both PI resolution and WM, and could explain the close relation between PI resolution and WM.

4.1.2. The neuroimaging study. The mechanism and neural basis of proactive control was examined by comparing hemodynamic signals immediately following list onsets in the directed forgetting task and the color recognition task. . The directed forgetting task is an often used PI task which may involve binding or item inhibition whereas the color recognition task only involves binding. The results showed that different brain regions were engaged in these two tasks. Specifically, the left inferior frontal areas showed greater activation in the directed forgetting task than the color recognition task, while the bilateral posterior parietal areas exhibited greater activation in the color recognition task than in the directed forgetting task. These findings suggest that item inhibition is involved in proactive control in the directed forgetting task, and this process is carried out by the left inferior frontal cortex. In contrast, the binding process which engages the posterior parietal regions is involved as the mechanism of proactive control in the color recognition task but is not involved in PI resolution in the directed forgetting task.

The mechanism and neural basis of reactive control was examined by comparing hemodynamic signals immediately following probe onsets of the interfering trials and the control trials in the directed forgetting task and the color recognition task. The left inferior frontal areas and the bilateral posterior parietal areas both exhibited greater activation for the interfering trials than the control trials. More importantly, the left inferior frontal areas overlapped with the left

inferior frontal area identified to be involved in inhibition via the contrast of proactive control, suggesting that inhibition is also involved in reactive control Moreover, the bilateral posterior parietal areas also have some overlap with the posterior parietal areas identified to be involved in binding via the contrast of proactive control, indicating that binding plays a role in reactive control as well. Taken together, these findings support episodic inhibition as a mechanism of reactive control. That is, PI arises due to conflict between appropriate and inappropriate item-context bindings and an inhibitory processing suppress the inappropriate links so that the appropriate links can be retrieved.

4.2. General Discussion

Findings of the neuroimaging study suggest that item inhibition is involved in proactive control of PI resolution while episodic inhibition is involved in reactive control. These findings first support the dual mechanism control model (Braver et al., 2007) since distinct proactive control and reactive control were detected, although the method of separating these two types of control mechanisms did not succeed in the Individual differences study. Moreover, the results of the neuroimaging study were also supported by the Individual differences study since individuals' performance on both inhibition (involved in item inhibition and episodic inhibition) and binding (involved in reactive control according to the episodic inhibition account) could predict the ability of PI resolution.

4.2.1. The item inhibition – episodic inhibition model of PI resolution. Rather than the dual inhibition model and the binding-episodic inhibition model, a new model, i.e., the item inhibition – episodic inhibition model is consistent with the findings of this thesis. An important assumption of this model is that the process of familiarity and the process of search are both engaged in recognition in the PI tasks. Therefore, item inhibition – a function that facilitates the

use of familiarity, and episodic inhibition – a function that facilitates the search process are both useful in resolving PI. When an interfering probe is presented, if its level of familiarity was reduced by item inhibition during the process of proactive control, the low level of familiarity would correspond to a negative response. Then it would be easier for episodic inhibition to select the appropriate item-context link during the process of search, since the appropriate link between the interfering probe and irrelevant context also corresponds to a negative response. In contrast, if item inhibition did not efficiently reduce the level of familiarity for the interfering probe (which corresponds to a negative response), it would be more difficult to select the appropriate item-context link during the process of search. As a result, a greater PI effect would arise.

Therefore, according to this model, the process of familiarity and the process of search are not two parallel processes that do not influence each other until each of them generates a response. Instead, these two processes interact and both provide some evidence for generating one signal and a final response. This idea (termed the single-process model) has been proposed and supported by some previous studies (e.g., Heathcote, Raymond, & Dunn, 2006; Humphreys, Bain, & Burt, 1989). Thus, PI is not caused by the conflict between the responses generated by the process of familiarity and the process of search, respectively. Rather, it results from the interference between appropriate and inappropriate item-context bindings during the single process of recognition that collects evidence from both familiarity and search.

4.2.3. Mechanisms of WM. Results of the individual differences study showed that WM capacity is correlated with abilities involved in binding, inhibition, storage and processing. These findings are consistent with many of the models of WM in that multiple components are involved in WM (Baddeley & Hitch, 1974; Baddeley & Logie, 1999; Cowan, 1988; 1995; 1999; Engle et al., 1999; Hasher & Zacks, 1988). Importantly, in addition to storage and processing,

control processes also play important roles in WM. Those control processes include not only inhibition (Hasher & Zacks, 1988), but also binding. In addition, these processes are dissociable and may not rely on a common attentional resource (Engle et al., 1999).

4.2.3. Limitations of the present studies. Some limitations exist in the present studies. First, the manipulation of proportions of interfering trials did not successfully separate proactive control and reactive control in the Individual differences study. More efficient methods to separate proactive control and reactive control should be used in further studies. For example, Braver et al. (2010) detected more engagement of proactive control after training older adults on the use of proactive control.

Second, since the inhibition tasks did not load significantly on a common factor, the latent variable approach could not be fully applied in the individual differences study. Therefore, different inhibition tasks should be used in future studies. For example, instead of using the letter flanker negative priming task that showed a restricted score range and low reliability, the Eriksen flanker task (Eriksen & Eriksen, 1974) and the nonverbal spatial Stroop task (Hamilton & Martin, 2005) that have been used repeatedly in previous studies and in which individuals showed a reasonable range of performance could be used to identified the latent factor of inhibition. If the latent factor of inhibition can be identified, the latent variable approach, such as structural equation modeling could be used in examining the contribution of inhibition to PI resolution and WM. This approach extracts common variance that reflects the shared process among tasks. Thus it is superior to the regression method based on single tasks in eliminating any task-specific component in the correlation.

Third, in the neuroimaging study, the contrast between the rehearsal and non-rehearsal conditions did not successfully identify regions involved in rehearsal. This contrast, compared to

the contrast between the rehearsal condition and fixations (this is the contrast used to examine whether regions involved in PI resolution overlapped with regions involved in rehearsal) is more appropriate since the visual stimuli were matched between two conditions. One possible reason for more activation observed in the non-rehearsal condition compared to the rehearsal condition is that participants were asked to remember the letter strings in the rehearsal condition. They might engage in more rehearsal of the letter strings during the block of the non-rehearsal condition to prevent forgetting. In future studies, participants should be asked to simply rehearse stimuli. The rehearsal localizer task could be placed in the beginning of the experiment, so that participants are more likely to follow the instruction of rehearsal even though such behavior would not be monitored by the experimenters.

4.2.4. Future directions. Some future directions have been discussed in Chapter 2. For example, the idea of separate inhibition functions for spatial vs. verbal information should be further tested using an individual differences approach. Importantly, to do so, the ability to simply process spatial and verbal material in tasks not involving inhibition should be controlled for. Then if spatial inhibition and verbal inhibition are indeed dissociable, such a finding would suggest there are distinct inhibitory processes that specially act upon verbal or spatial materials. In addition, different PI tasks that do not require any spatial processing (such as tasks with auditory presentations) should be tested to examine whether non-spatial inhibition (e.g., the process measured in the Stroop task) would also be involved in PI resolution.

In addition, based on the finding that both the inferior frontal area and the posterior parietal areas are involved in reactive control, I made the inference that the inhibitory process (carried out by the inferior frontal area) suppresses the inappropriate binding relations (involving

the posterior parietal areas). To more directly test this idea, the structural and functional connections between these two regions should be examined in future studies.

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Appendix

Correlations between variables.

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. DF_high[1]	_																	
2. RN_high[1]	.33**	_																
3. Pat_high[1]	.19*	.12	_															
4. DF_low[1]	.33**	.10	.02	_														
5. RN_low[1]	.21*	.24**	.02	.19*	_													
6. Pat_low[1]	-.04**	.05	.05	.01	.09	_												
7. RM_mem	.37**	.22*	.17	.22*	.35**	-.01	_											
8. RM_nomem	.33**	.14	.10	.21*	.25**	-.03	.50**	_										
9. Local	.34**	.10	.03	.24*	.17	.10	.26**	.39**	_									
10. Stroop	.10	.14	.04	.06	.13	-.07	.19*	.14	.06	_								
11. Saccade	.29**	.17	.16	.17	.04	.16	.31**	.20*	.18*	.06	_							
12. Flanker	.19*	-.07	-.22*	.14	.12	-.05	..03	.01	.12	.04	.01	_						
13. OSpan	.06	.10	.003	.22*	.24**	-.04	.25**	.10	.26**	.26**	.21*	.13	_					
14. RSpan	.19*	.12	.10	.01	.20*	-.14	.27**	.23*	.26**	.05	.22*	.02	.56**	_				
15. SSpan	.10	.05	.08	.06	.07	-.09	.27**	.21*	.24**	.09	.26**	-.02	.38**	.31**	_			
16. DSpan	-.01	.12	-.11	.01	.11	-.11	.07	.15	.06	.23**	.09	-.02	.31**	.32**	.27**	_		
17. CSpan	.27**	.26**	.17	.14	.31**	-.02	.42**	.28**	.27**	.19*	.08	.03	.19*	.24**	.14	.18	_	
18. MSpan	.13	-.01	.15	.06	.004	-.29**	.16	-.01	.21*	.11	.09	-.01	.08	.14	.32**	.12	.01	_

** $p < .01$; * $p < .05$; [1] regression residuals of the composite scores for the intrusion condition on the control condition; DF_high: high interference version of the directed forgetting task; RN_high: high interference version of the word recent negative task; Pat_high: high interference version of the pattern recent negative task; DF_low: low interference version of the directed forgetting task; RN_low: low interference version of the word recent negative task; Pat_low: low interference version of the pattern recent negative task; RM_mem: the memory rhyme monitoring; RM_nonmem: the nonmemory rhyme monitoring task; Local: the local recognition task; Stroop: the Stroop task: Saccade: the saccade-antisaccade task: Flanker: the letter flanker negative priming task; OSpan: operation span; RSpan: reading span; SSpan: symmetry span; DSpan: digit span: CSpan: category span; MSpan: matrix span.